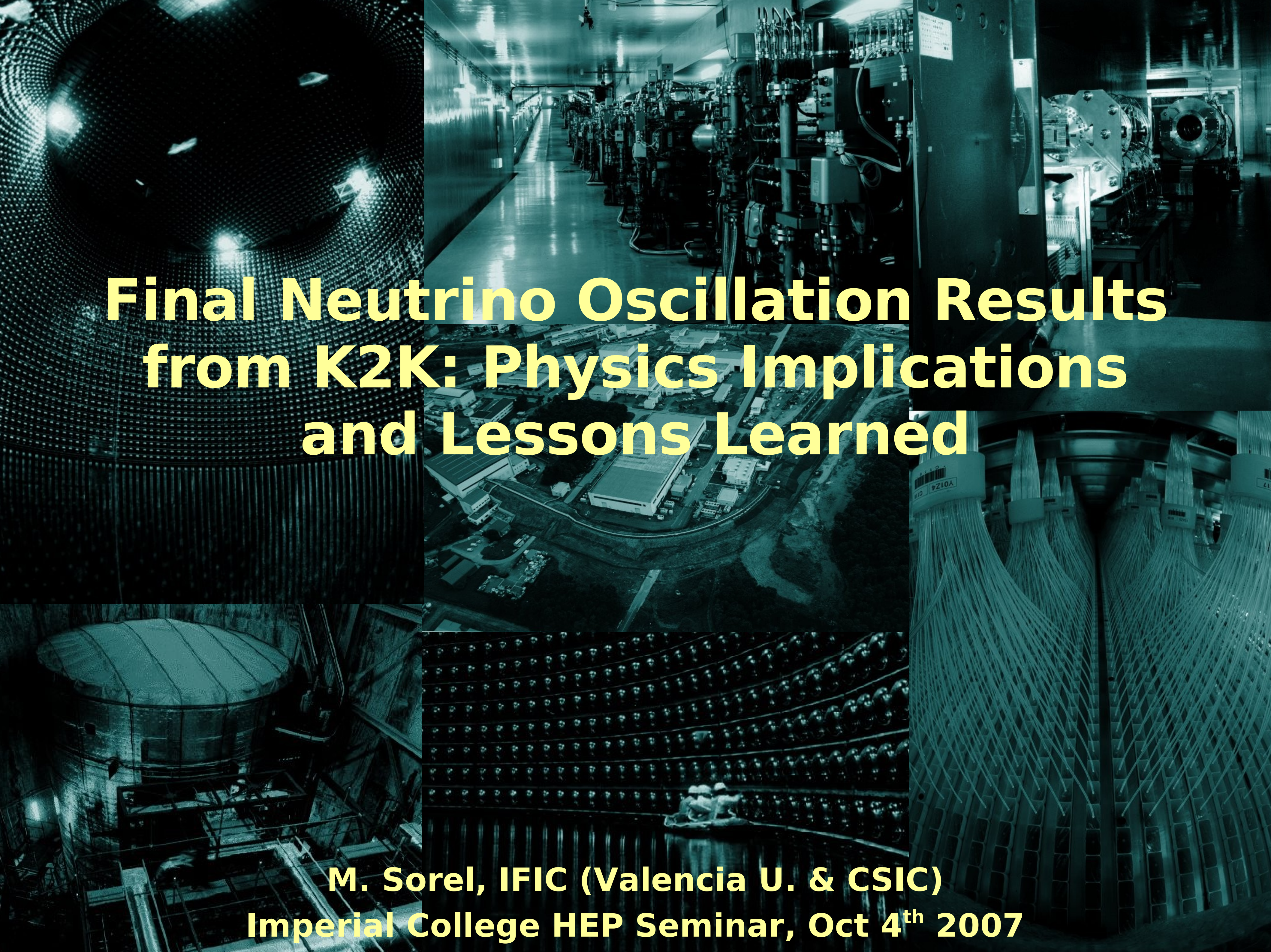


Final Neutrino Oscillation Results from K2K: Physics Implications and Lessons Learned

M. Sorel, IFIC (Valencia U. & CSIC)

Imperial College HEP Seminar, Oct 4th 2007

Outline

- Neutrino Oscillations
- The K2K long-baseline neutrino oscillation experiment
- Confirmation of atmospheric $\nu_\mu \to \nu_\tau$ oscillations
- Search for sub-leading $\nu_\mu \to \nu_e$ oscillations

Outline

- Neutrino Oscillations
- The K2K long-baseline neutrino oscillation experiment
- Confirmation of atmospheric ν_μ -> ν_τ oscillations
- Search for sub-leading ν_μ -> ν_e oscillations

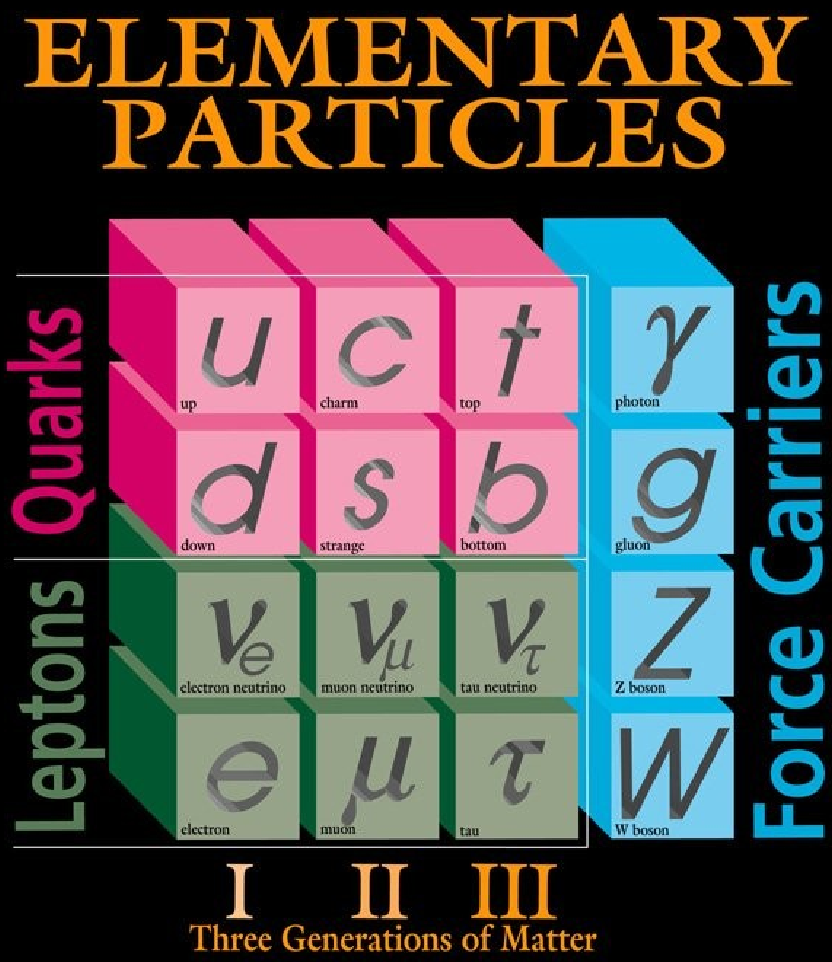
- *K2K contributions to our understanding of neutrino masses and mixings*
- *Lessons learned of relevance to other, near-future, oscillation experiments*

Neutrino

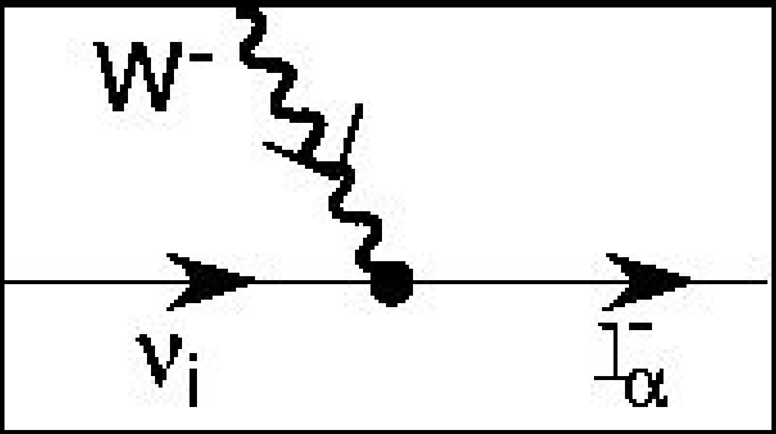
Oscillations

Neutrinos: What We Know

- Lightest known fermions
- No color (no QCD interactions)
- No electric charge
- Observable via weak interactions
- Paired with charged leptons in weak isodoublets
- Three light “active” neutrino families
- Non-zero masses and mixings



Neutrino Mixing



- Flavor eigenstates $|\nu_\alpha\rangle$ $(\alpha = e, \mu, \tau)$
  $\Rightarrow$ identified with charged lepton:
  - Produced in decay with lepton l^+_α
  - Produces lepton l^-_α in CC interactions
- Mass eigenstates $|\nu_i\rangle$
  $\Rightarrow$ determines free particle evolution

- Neutrino mixing: flavor and mass eigenstates are distinguishable
- Flavor/mass eigenstates related by unitary PMNS mixing matrix:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle$$

- Mass splittings and mixings determined via neutrino oscillation experiments

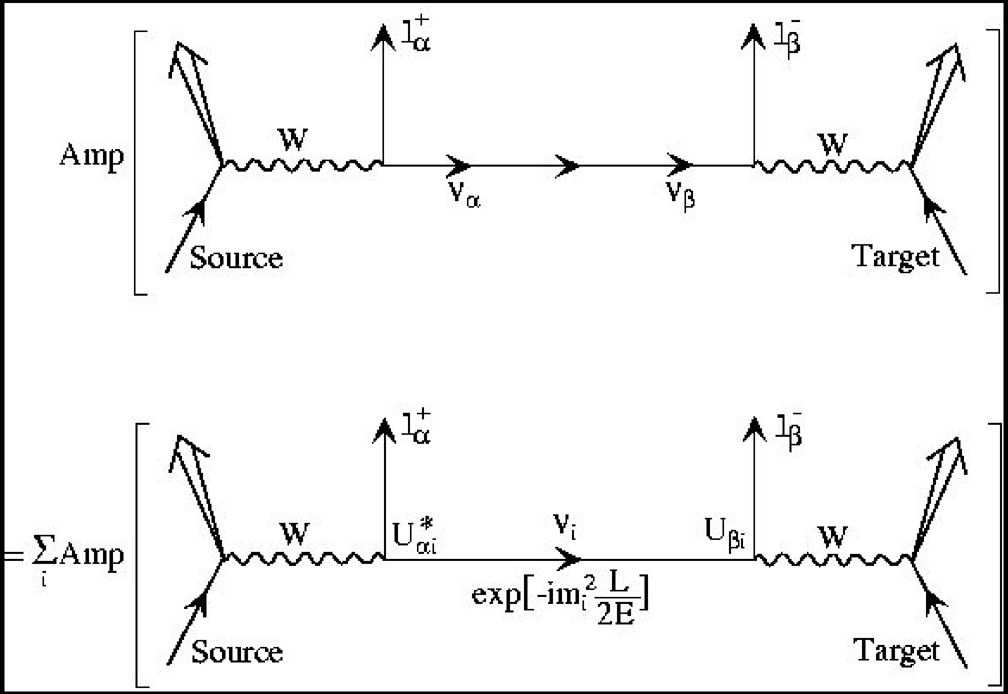
Neutrino Flavor Oscillations

- **Appearance**:

  start with flavor α and observe some different flavor β after some time/distance

- **Disappearance**:

  start with known amount of ν_α, find less ν_α later



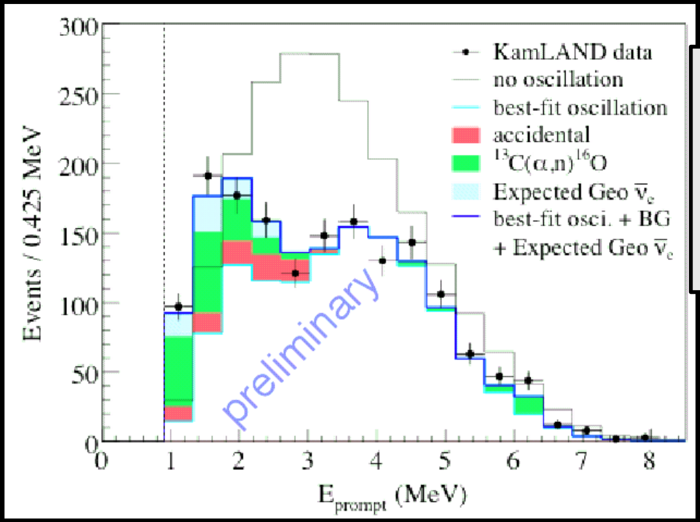
- **Oscillation probability**:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left[1.27\,\Delta m^2_{ij}(L/E)\right]$$

$$+2\sum_{i>j} \Im\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left[2.54\,\Delta m^2_{ij}(L/E)\right], \text{ where: } \Delta m^2_{ij} \equiv m^2_i - m^2_j$$

Non-zero and non-degenerate masses, $U \neq 1$ ⇒ neutrino oscillations

Neutrino Oscillation Signatures at Δm^2_{sol} and Δm^2_{atm}

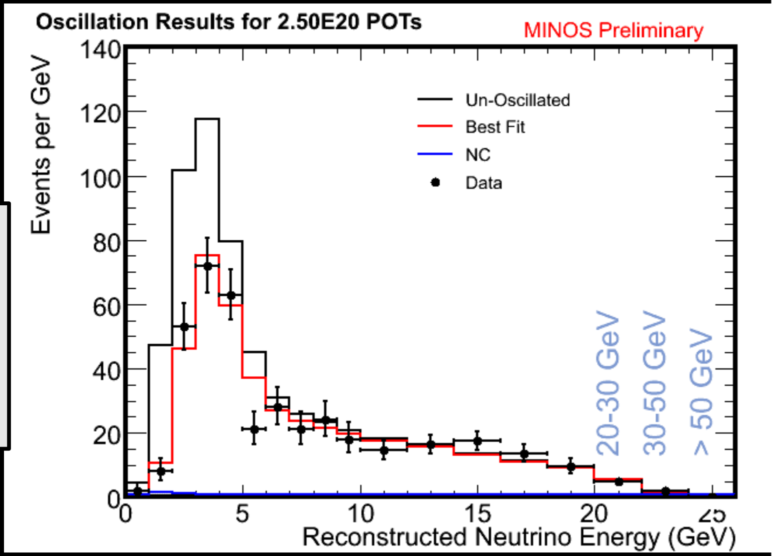


Solar Neutrino Oscillations

- Deficit of nues observed from the Sun
Homestake, SAGE, GALLEX/GNO, Super-K, SNO
- Confirmed by KamLAND (reactor nuebars)

Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of atmospheric numus
Kamioka, Super-K, Soudan, MACRO
- Confirmed by K2K and MINOS (accelerator numus)



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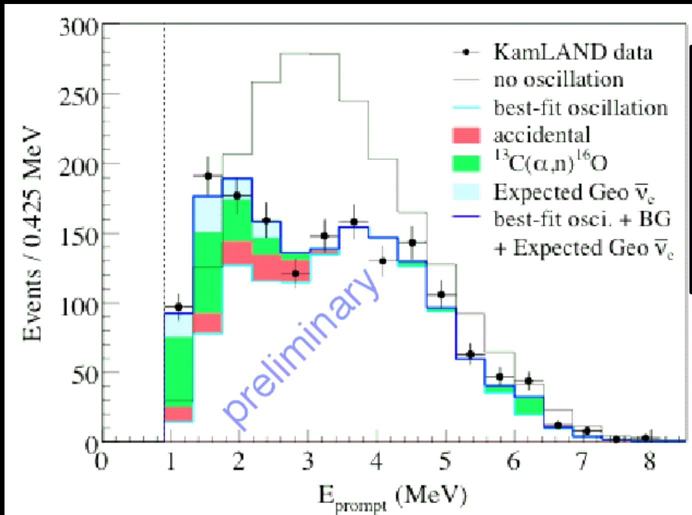

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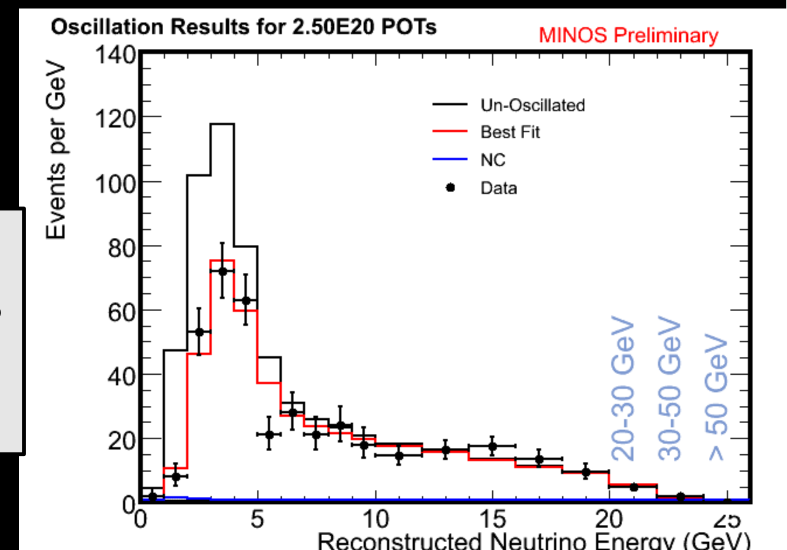

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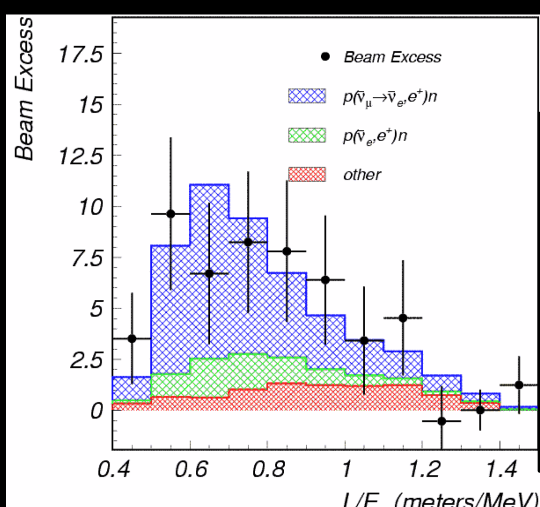


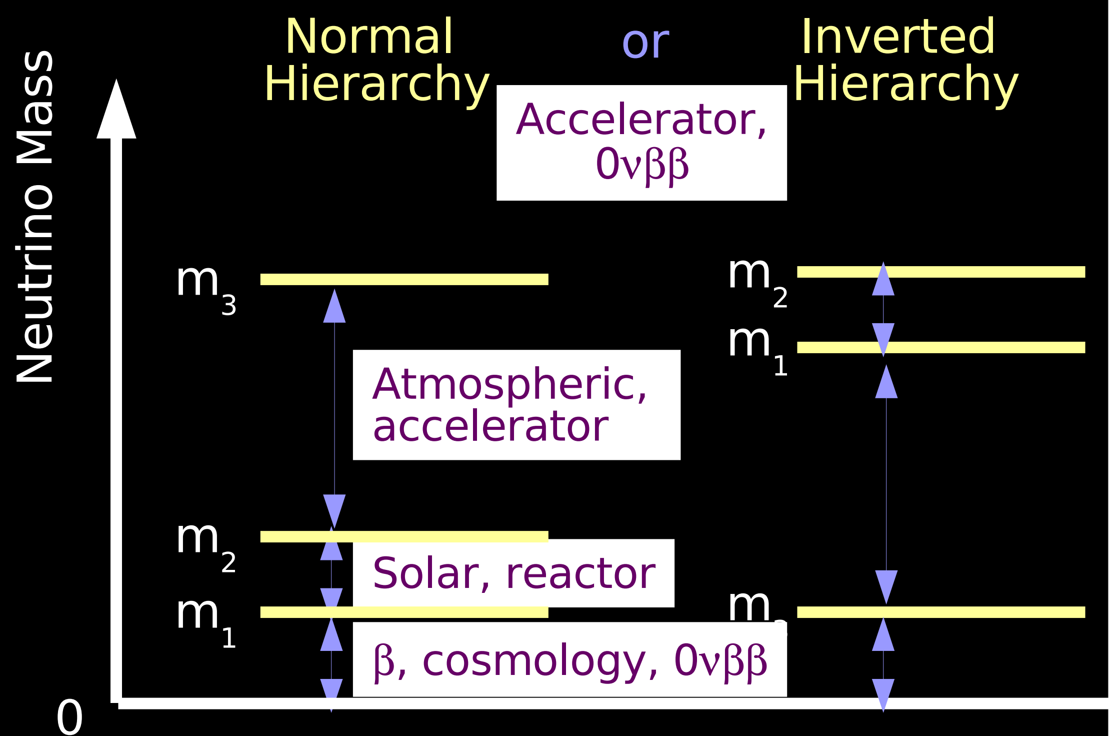
LSND Neutrino Oscillations ?

- Excess of nuebars in numubar beam produced from muon decay-at-rest
- Simplest neutrino oscillation interpretation of this excess recently excluded by MiniBooNE
- In the following, assume LSND not due to oscillations

Three-Neutrino Formalism

Neutrino mass and mixing parameters:

- 3 neutrino masses: m_1, m_2, m_3
- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac phase: δ
- 2 additional phases if Majorana: α, β



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric, accelerator | Accelerator, reactor | Solar, reactor | 0νββ

Three-Neutrino Parameters (1σ errors)

- 3 neutrino masses:

$\Delta m^2_{21} = (7.9 \pm 0.28)\cdot 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{31}| = (2.6 \pm 0.2)\cdot 10^{-3}\ \mathrm{eV}^2$

$\mathrm{sgn}(\Delta m^2_{31})$ unknown

$m_{light} < 1$ eV

- 3 mixing angles:

$\theta_{12} = 33.7 \pm 1.3$ deg

$\theta_{23} = 43.3 \pm 4.1$ deg

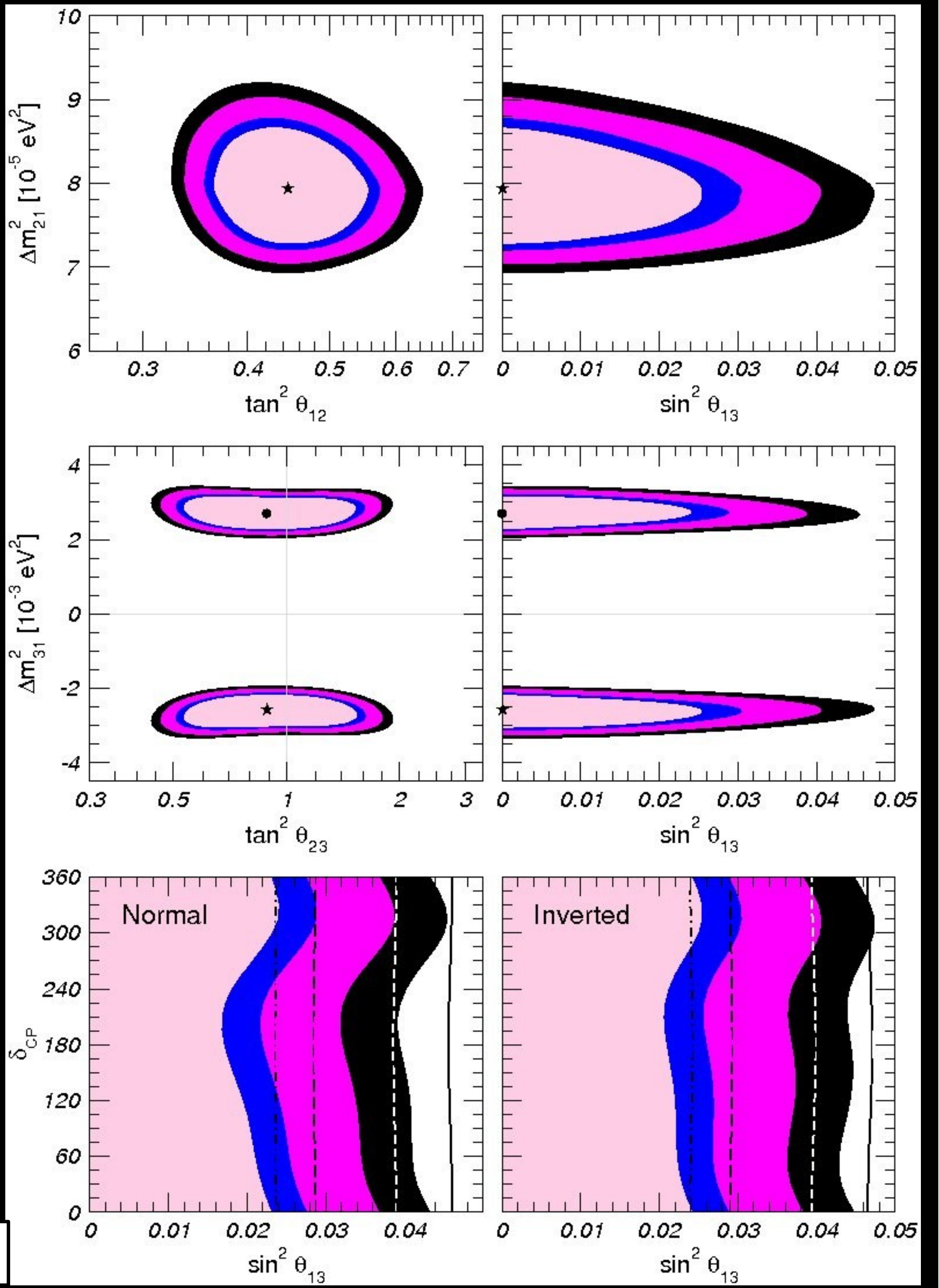
$\theta_{13} < 5.2$ deg

- 1 Dirac phase:

δ unconstrained

- 2 additional phases if Majorana:

α, β unconstrained



Ref: Gonzalez-Garcia, Maltoni, arXiv:0704.1800

Neutrino Open Questions

Issues	Questions	Theorists' Poll
Number of Light Neutrinos	3 active + ? steriles	Three
Majorana vs Dirac	$\nu=\bar{\nu}$, 2 vs 4 states per ν, lepton number violation	Majorana
Masses	degenerate, normal/inverted	Seesaw
Mixings	θ_{13}, $\theta_{23}=\pi/4$, U real vs complex, CP violation, leptogenesis	???
Exotics	Non-standard interactions, CPT violation, decays, μ-moment, etc.	None

From S. Parke (FNAL): *"At least one theoretical prejudice is wrong"*

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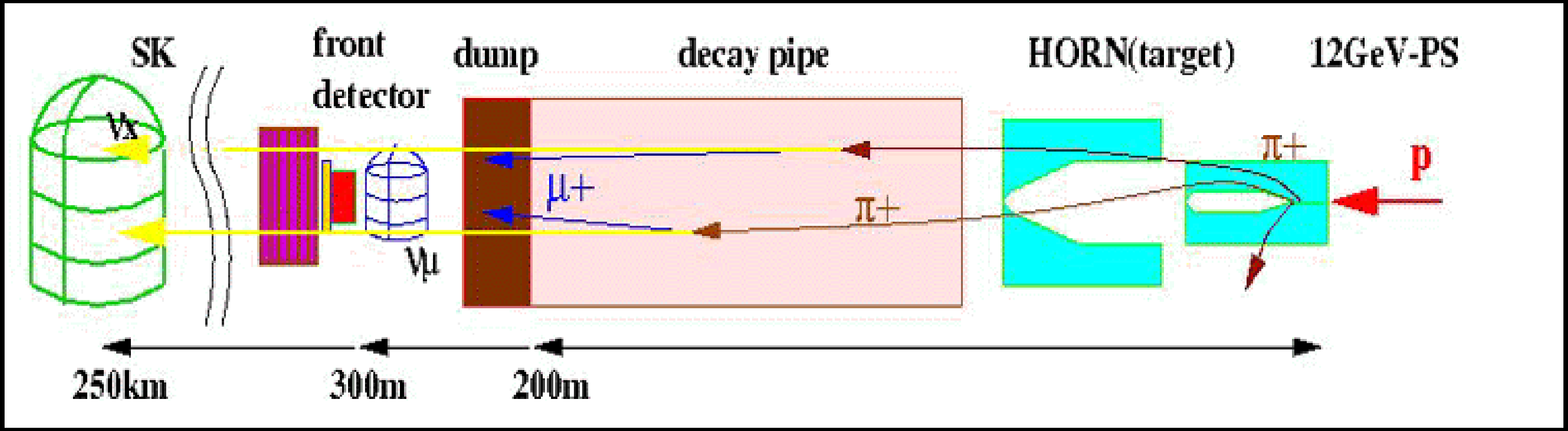
K2K contributions

The K2K long-baseline neutrino oscillation experiment

The K2K Experiment

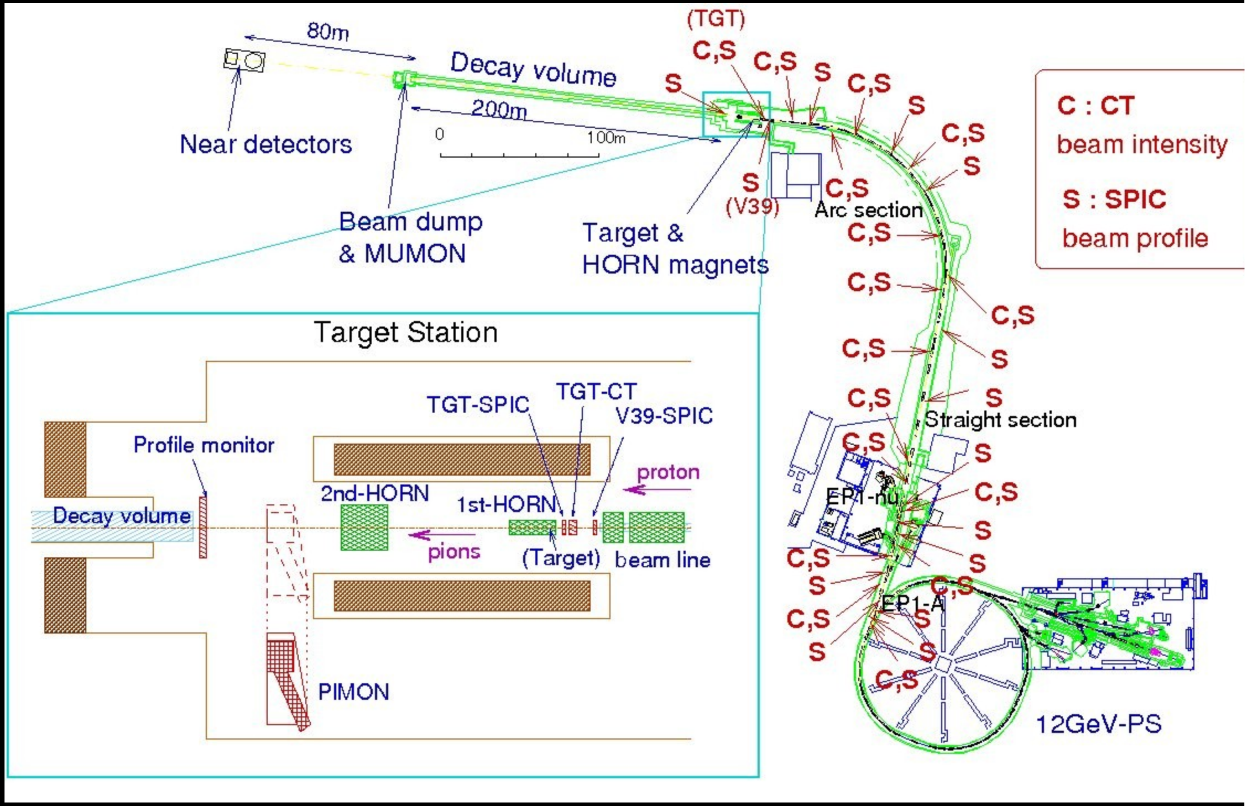


- Goals: confirmation of atmospheric $\nu_\mu \to \nu_\tau$ oscillations, search for sub-leading $\nu_\mu \to \nu_e$ oscillations, precision neutrino-nucleus interaction measurements
- Proposed in 1995, physics data-taking period: June 1999 – November 2004

K2K Collaboration

- 10 countries, 35 institutions, ~200 collaborators

Neutrino Beam



Primary Beam:

- 12 GeV protons from KEK PS
- 1.1 μs spill, every 2.2 s
- Current transformers and SPICs: beam intensity, profile, position
- 10^{20} protons delivered to target

Secondary Beam:

- Few GeV pions from the interactions of protons with Al target
- Two-horn system focuses positive particles, increasing flux by ~ x20
- Gas Cherenkov detector (PIMON): pion momenta and angles after horns

Neutrino Beam:

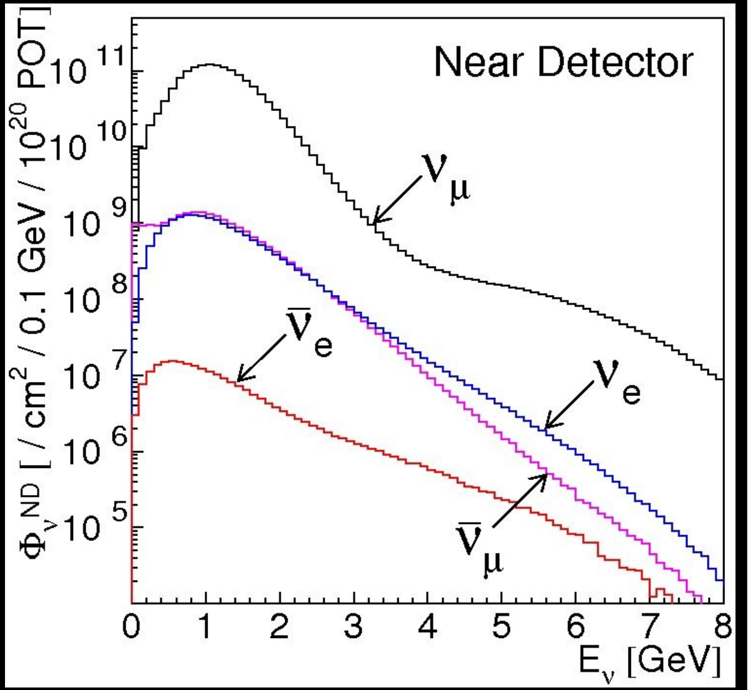
- Mesons and muons decay in 200 m long decay volume filled with He gas
- Beam dump stops all particles except neutrinos
- Measure profile of muons reaching beam dump

Neutrino Fluxes

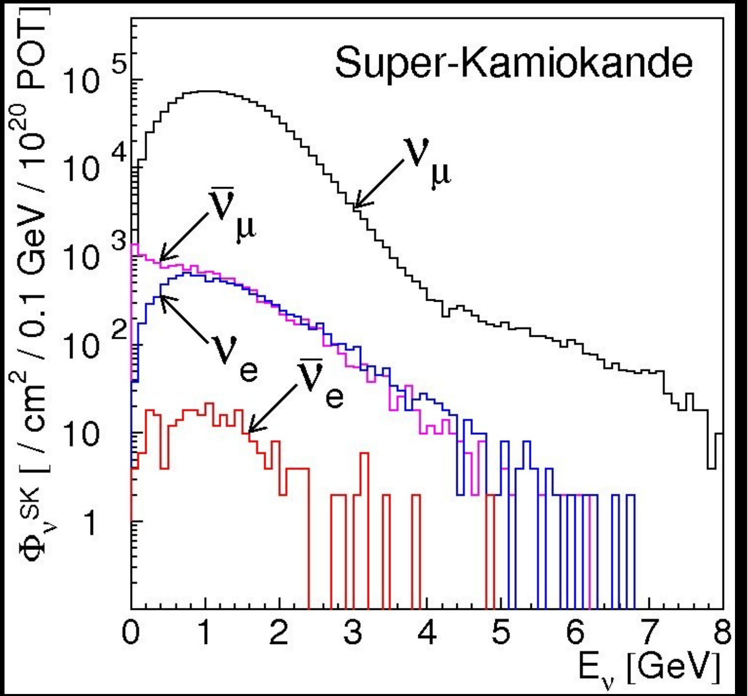
- Fluxes at near detector location:
  - Expected flavor content:

$$\nu_e : \overline{\nu_e} : \nu_\mu : \overline{\nu_\mu} \; = \; 1.3 : 0.02 : 97.3 : 1.5$$

  - ν_e contamination in the beam validated via near detector measurements
  - Flux-averaged neutrino energy: 1.3 GeV
  - Energy shape predictions tuned via near detector spectrum fit

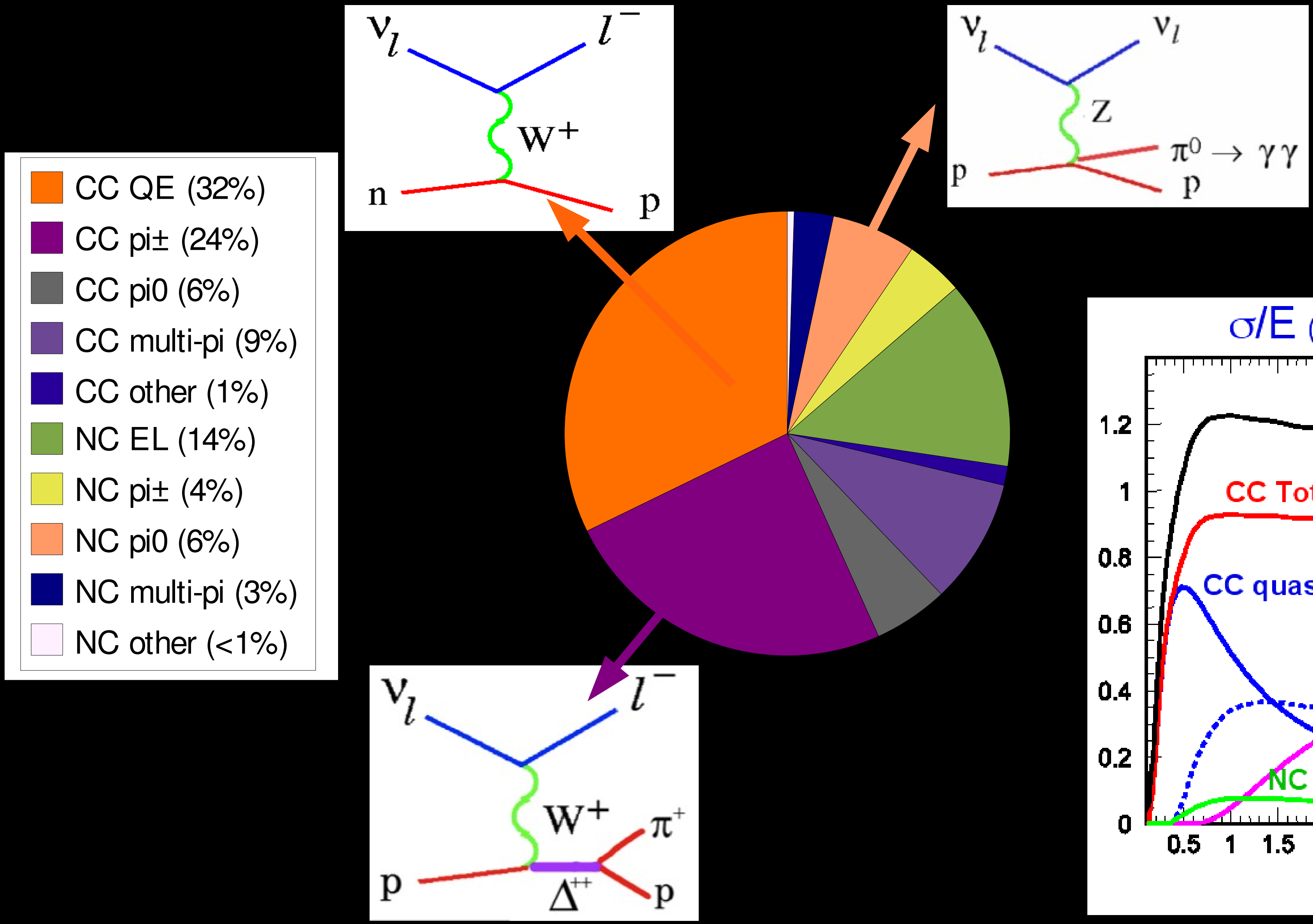


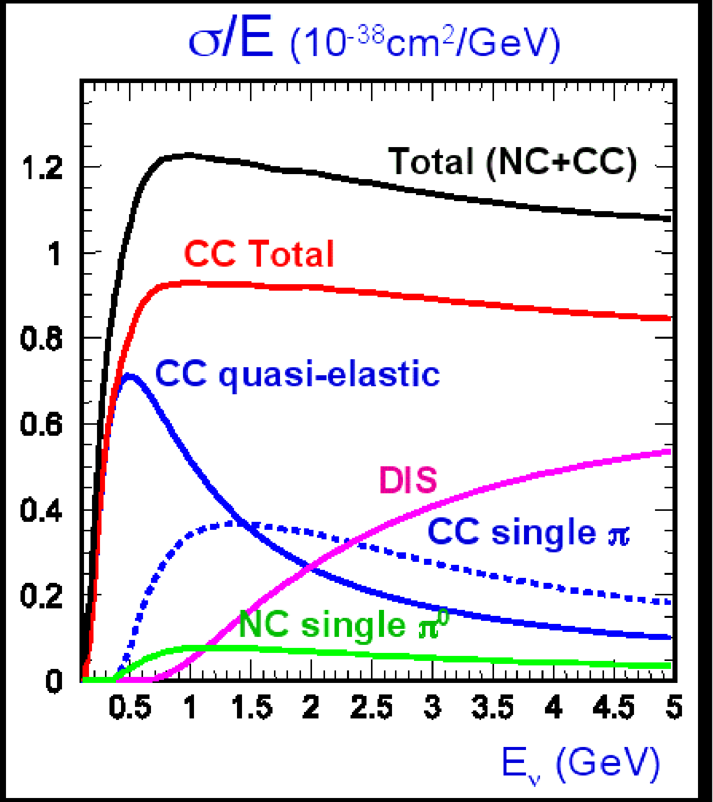
- Fluxes at far detector location:
  - Flux per unit area about 10^6 smaller
  - Similar flavor content
  - Non-negligible differences in neutrino energy shape
  - Direction pointing to Super-Kamiokande within ±1 mrad for the entire run period, as measured by muon monitors



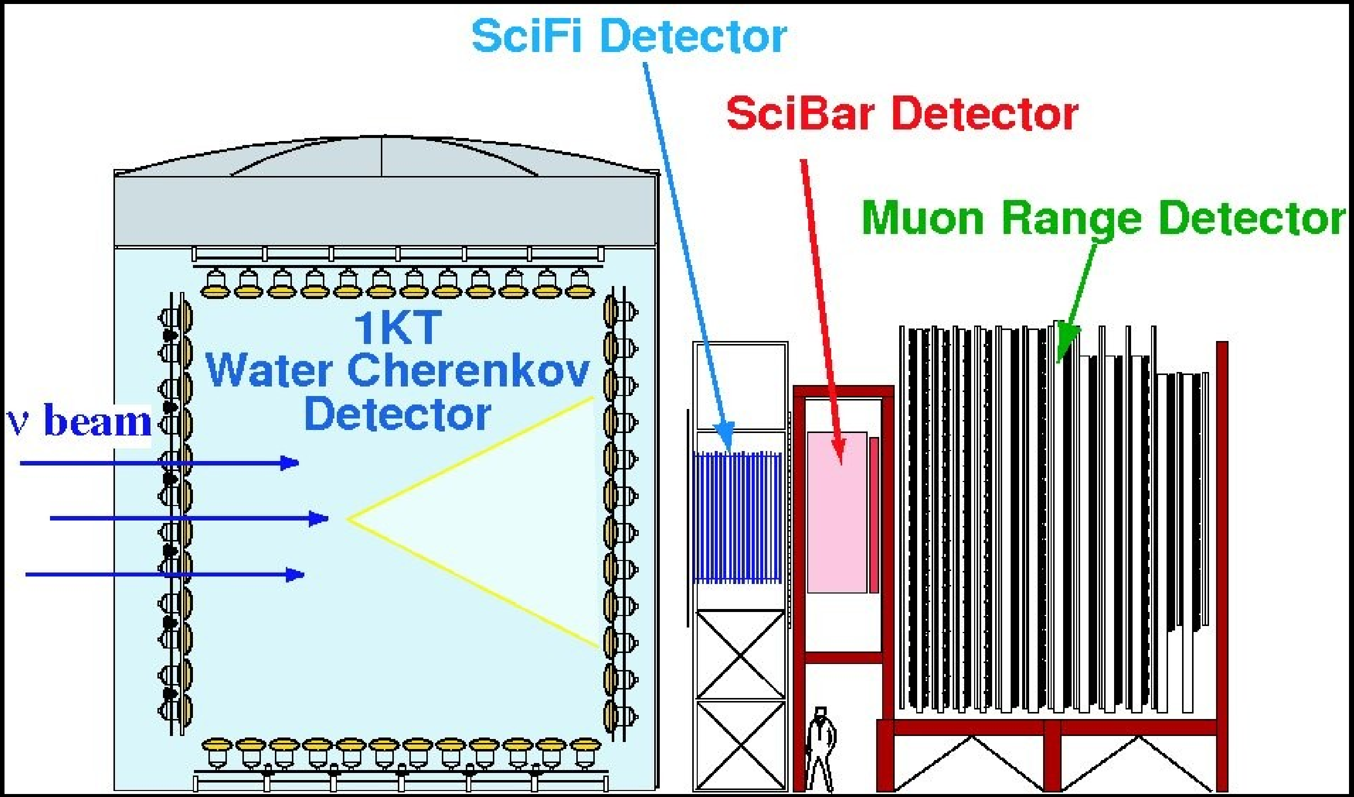
Neutrino Interactions

- Modeled with NEUT simulation, predictions tuned via near detector measurements





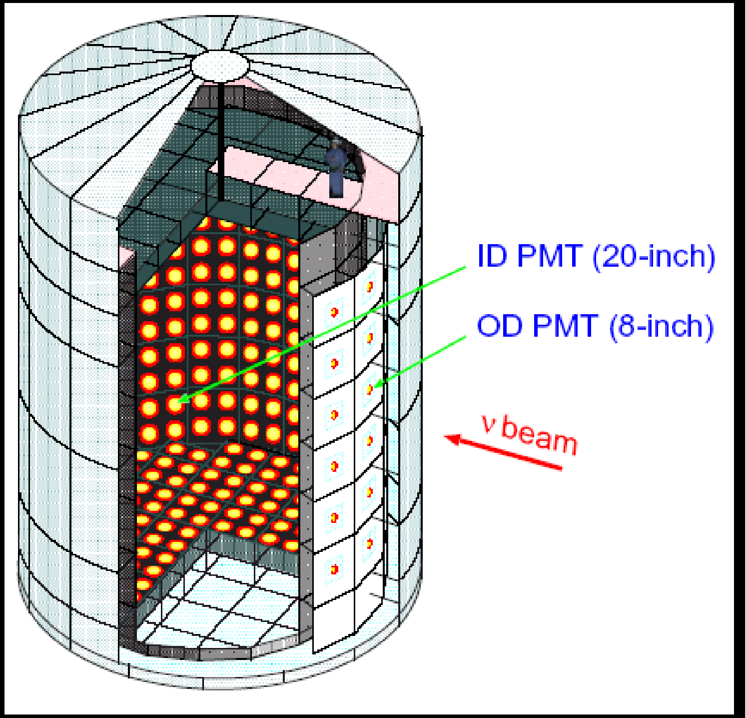
Near Detectors

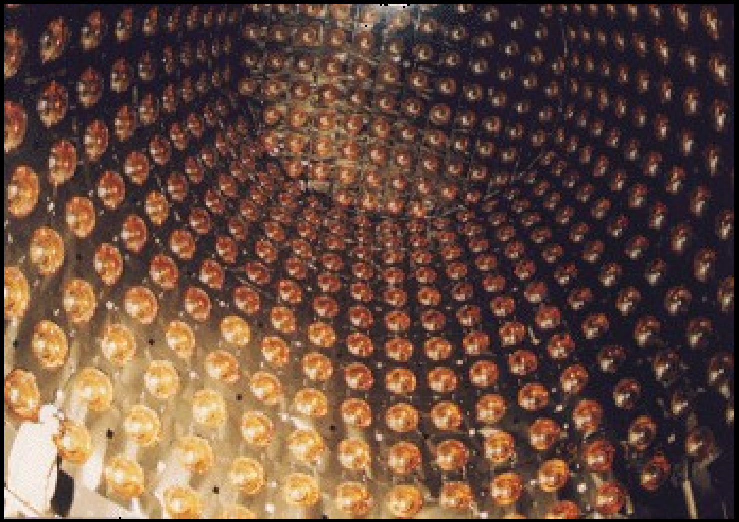


- Located 300 m downstream of the production target, along beam axis
- Near detectors comprise a 1 kton Water Cherenkov detector (1KT), and a fine-grained detector system (FGD)
- The FGD consists of the SciFi, SciBar, and MRD detectors. Until summer 2003: lead glass calorimeter in place of SciBar
- Purpose: measure beam direction, flux, energy spectrum, and interaction cross-sections before neutrino oscillations

1 kton Water Cherenkov Detector (1KT)

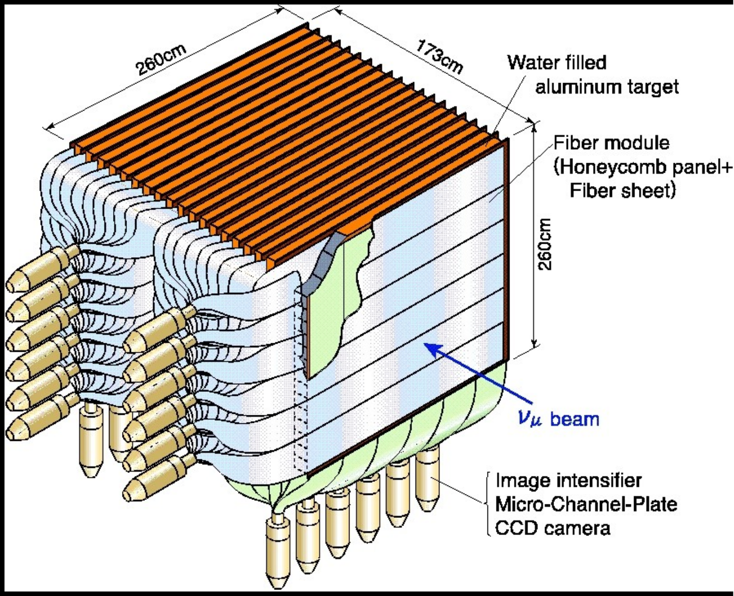
- Miniature version of Super-Kamiokande: same neutrino interaction target material, instrumentation, reconstruction algorithms
- Cylindrical tank, 10.8 m in diameter and 10.8 m in height, filled with ~1000 tons of pure water
- Purpose: rate and energy spectrum measurement, study neutrino-water interactions
- Outer detector (OD) optically separated from inner detector (ID), to tag tracks originating upstream, and through-going/stopping cosmic ray muons
- From Cherenkov light, reconstruct:
  - neutrino interaction vertex
  - number of tracks producing Cherenkov rings
  - track's 3-momenta
  - showering ($e^{\pm}$, γ) or non-showering ($\mu^{\pm}$, $\pi^{\pm}$) track type
  - fully contained or partially contained event tracks

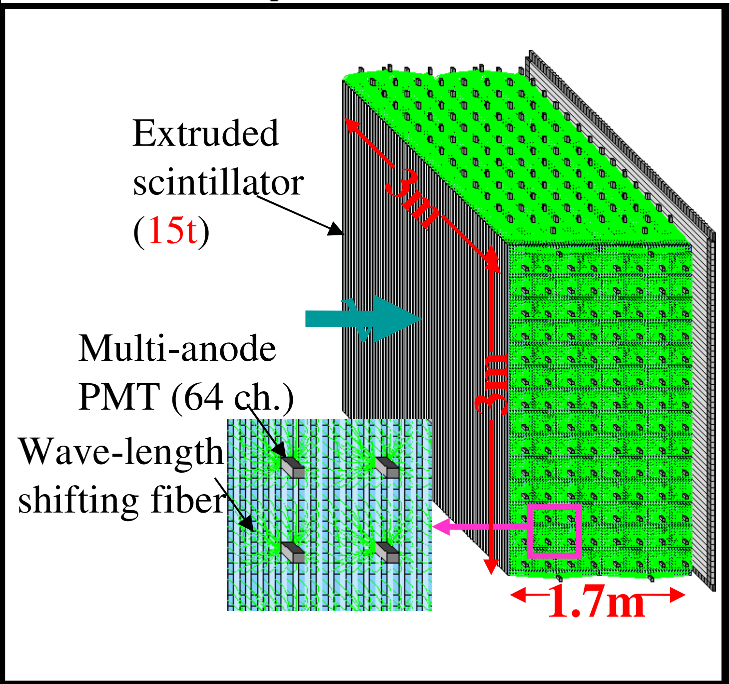




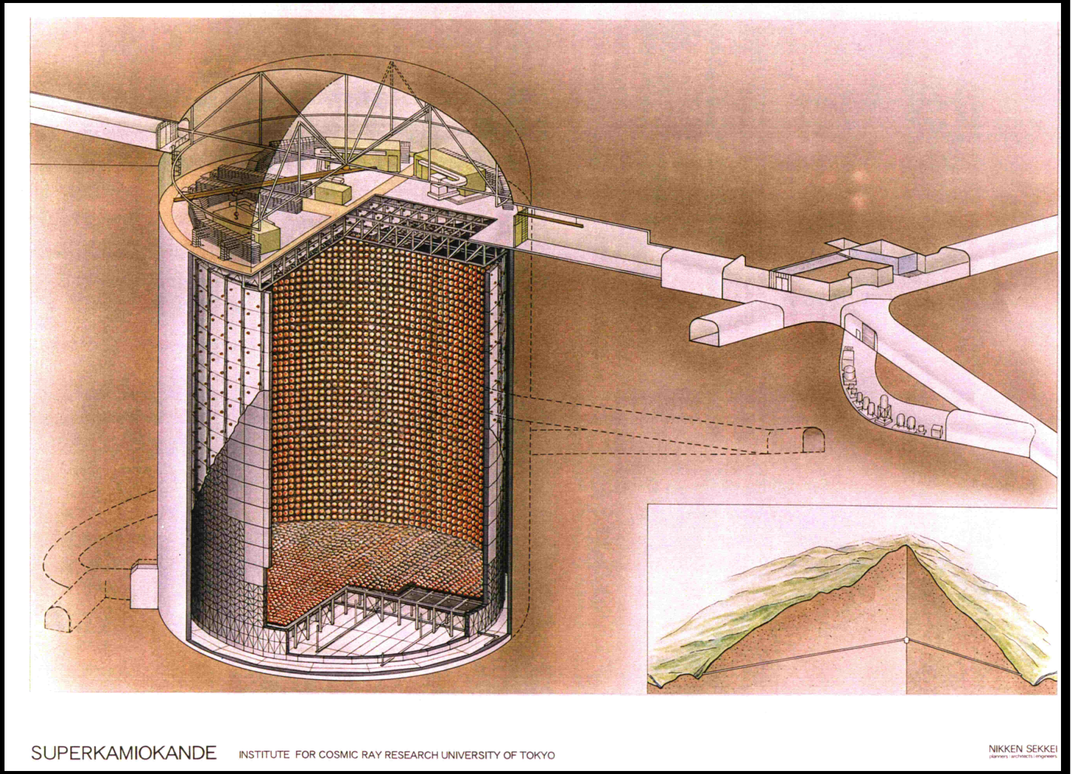
Fine-Grained Detector System (FGD)

- Scintillating Fiber (SciFi) detector:
  - 6 ton tracking detector with water target layers, interleaved with layers of scintillating fibers sheets
  - Purpose: energy spectrum measurement, discriminate quasi-elastic from inelastic events, sensitive to higher energy events than 1 kton
- Scintillating Bar (SciBar) detector:
  - 15 ton, fully active and highly segmented tracking detector, with C_8H_8 target
  - Purpose: energy spectrum measurement, efficient study of low momentum particles
  - Tracker followed by Electron Catcher (EC): beam ν_e contamination, and neutrino-induced π^0production
- Muon Range Detector (MRD):
  - Iron absorber layers sandwiched in between drift-tubes, 915 tons total mass
  - Purpose: monitor beam direction, profile, spectrum; identify muons produced in upstream detectors

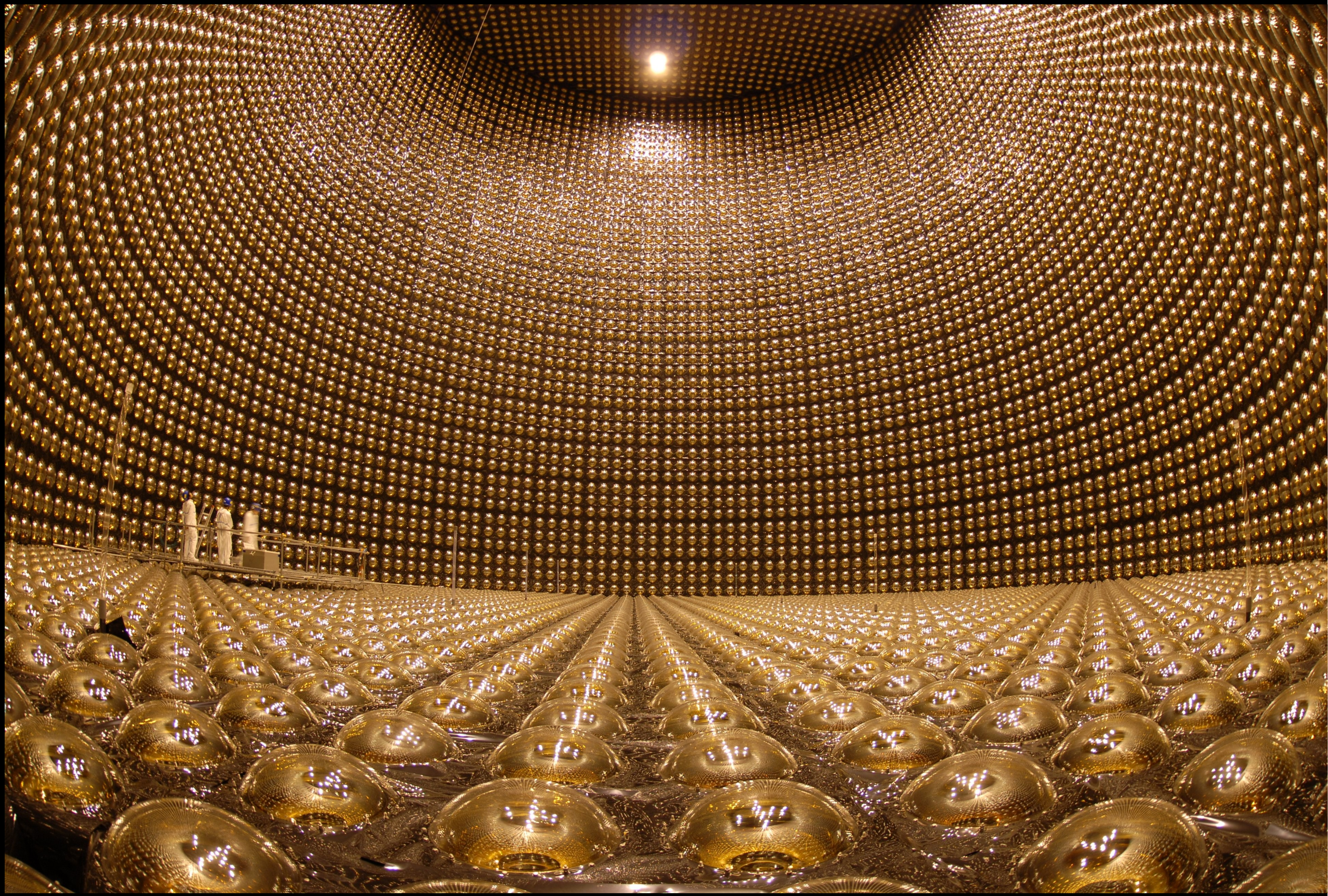




Far Detector:
Super-Kamiokande (SK)



- World's largest water Cherenkov detector: cylindrical shape, 41 m in height, 39 m in diameter, housing 50 kton of water
- As 1KT, separated into ID and OD parts
- ID viewed by 11,146 (5,182) 20-inch PMTs during K2K-I (K2K-II) phase
- Reconstruct interaction vertex, number of tracks producing Cherenkov rings, tracks' 3-momenta, e-like/μ-like track properties, fully or partially-contained interactions
- Fiducial volume: 22.5 kton
- GPS system: synchronize timing of beam spill between KEK and SK, to distinguish beam neutrino interactions from cosmic ray – induced activity



Confirmation of Atmospheric

ν_μ -> ν_τ Oscillations

Muon Neutrino Survival Probability

- Probability that a neutrino produced with muon flavor and energy E will be detected as a neutrino of the same muon flavor, after propagating a distance L = 250 km

- To first order at the atmospheric L/E scale, can be described by a two-neutrino system:

$$\mathbf{P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2 (1.27\Delta m^2 L/E)}$$

  - Δm^2 is the mass squared difference between the two mass eigenstates

  - θ sets the amount of muon flavor in each of the two mass states, the second flavor content other than the muon one being unobservable (say, tau or “sterile” flavor). Electron neutrinos do not participate in the oscillations.

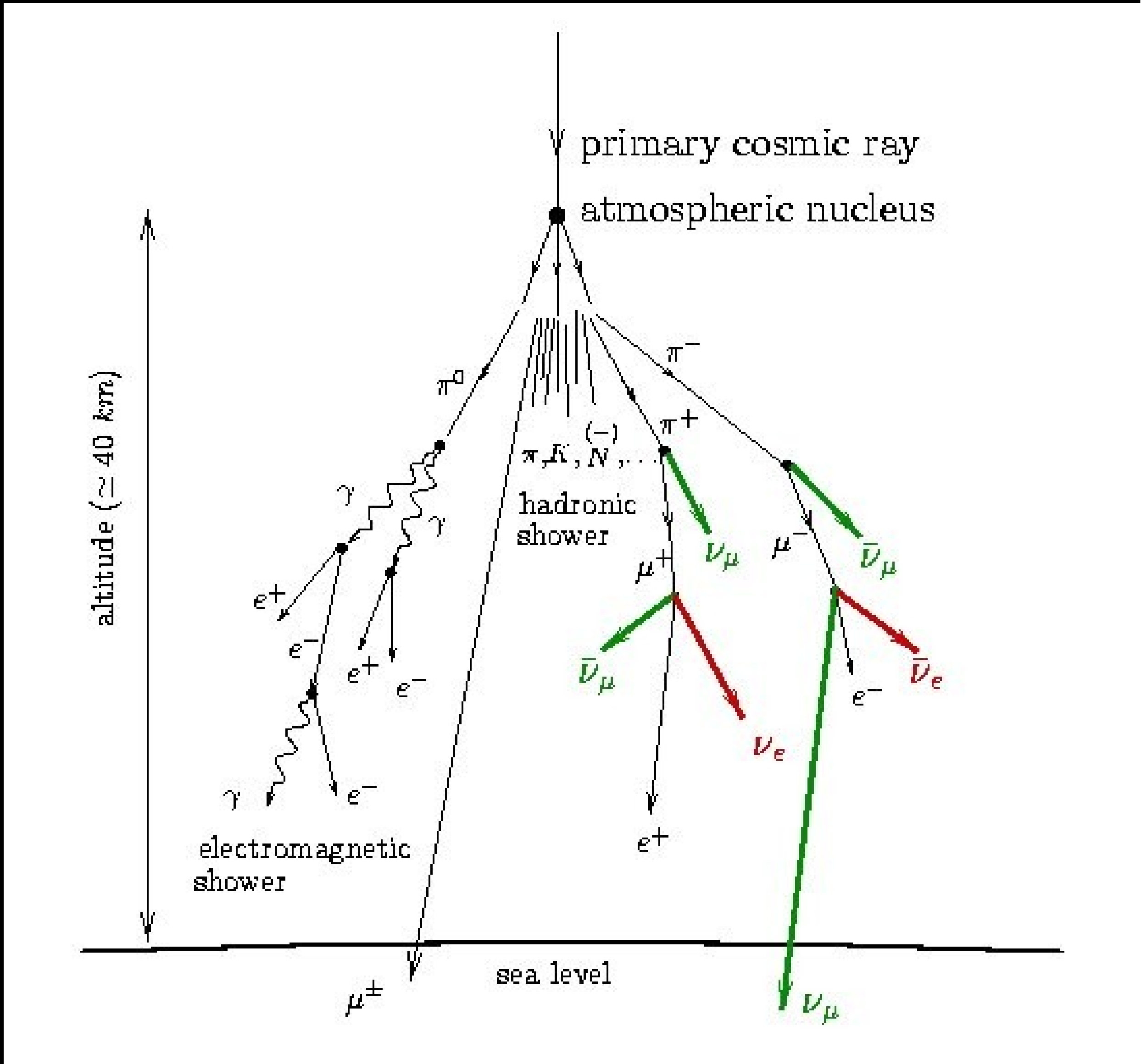
- Two-neutrino parameters can be associated to 3-neutrino mixing ones as:

$$\mathbf{\Delta m^2 \to \Delta m^2_{31},\ \theta \to \theta_{23}}$$

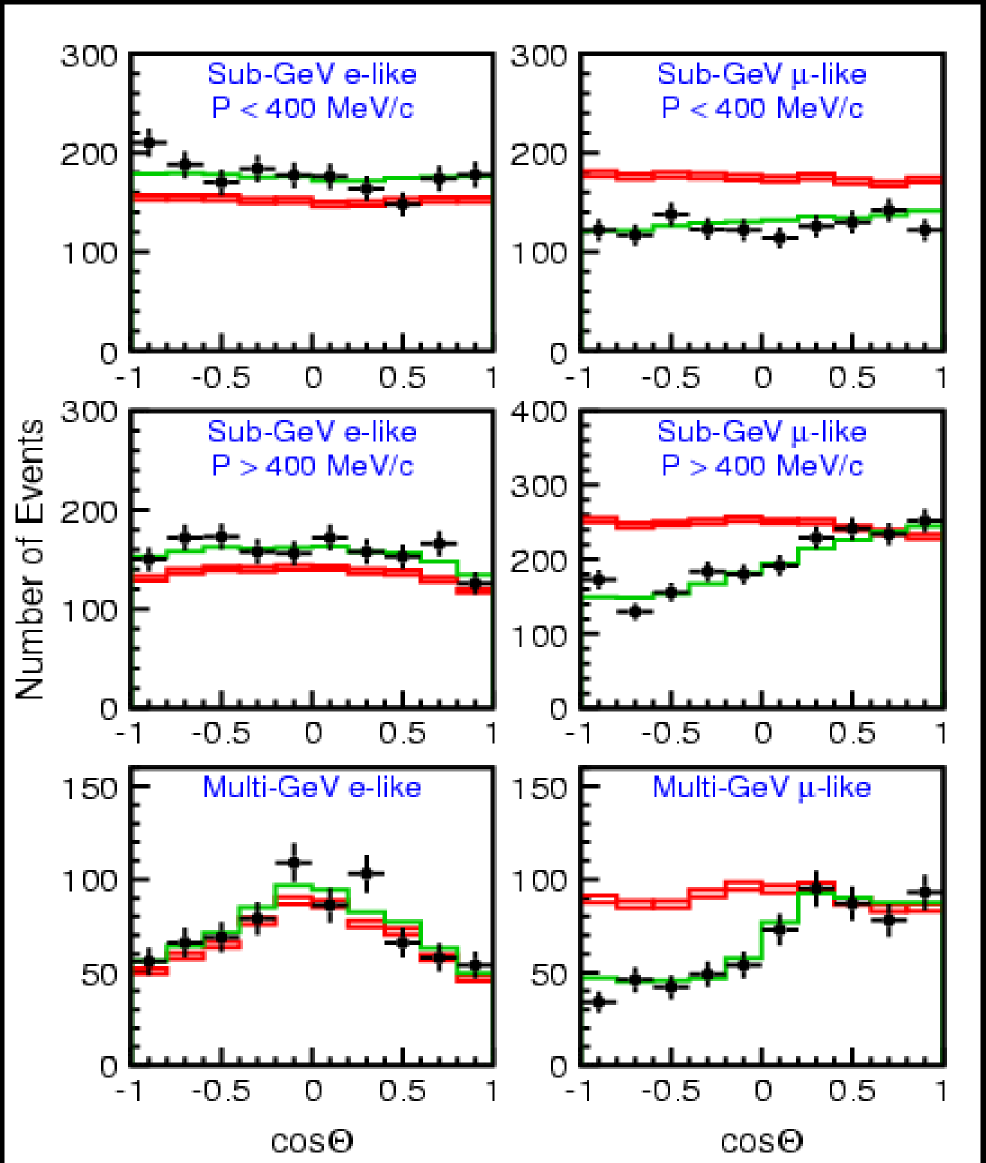
- Corrections due to small parameters Δm^2_{21}L/E and θ_{13}, and matter density, are small

Atmospheric Neutrinos

- Neutrinos produced via the interactions of cosmic rays with nuclei in the atmosphere
- ν_e/ν_μ unoscillated flux ratio can be predicted with good accuracy
- Neutrinos observed in large underground detectors, to minimize cosmic ray muon backgrounds



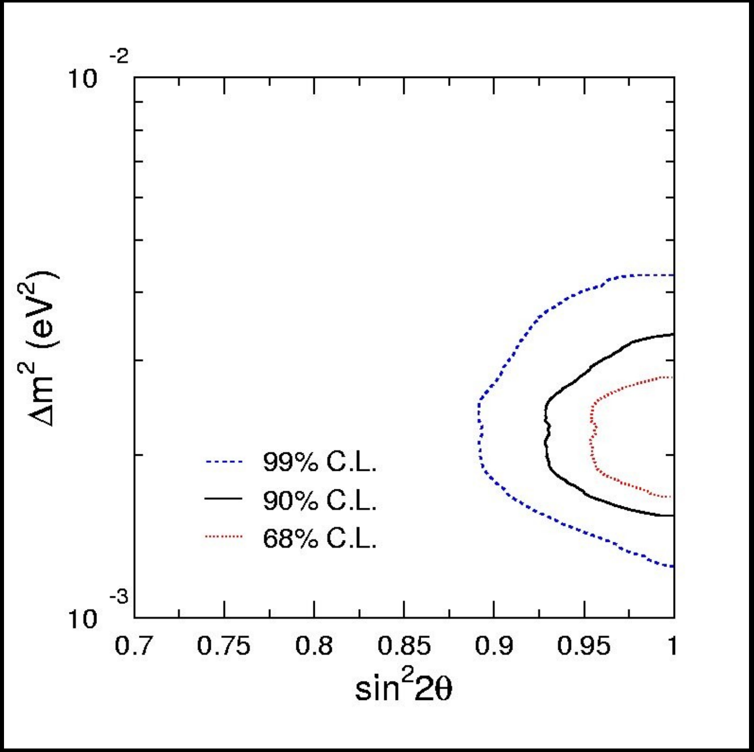
Atmospheric Neutrino Oscillations



Ref: SK Coll, PRD71:112005 (2005)

- Zenith angle- and energy-dependent deficit of muon neutrinos with respect to no-oscillations predictions
- Data well described by neutrino oscillations hypothesis, with parameters:

$$\Delta m^2 \simeq 2.6 \cdot 10^{-3}\ \mathrm{eV}^2,\ \sin^2 2\theta_{\mu\mu} \simeq 1$$



K2K Disappearance Analysis Strategy

Near (KEK)

Measure number of neutrino interactions and (p_μ, θ_μ) distributions

Interaction Simulation

Measure flux, energy spectrum, non-QE interactions

Beam Simulation

Far (SK)

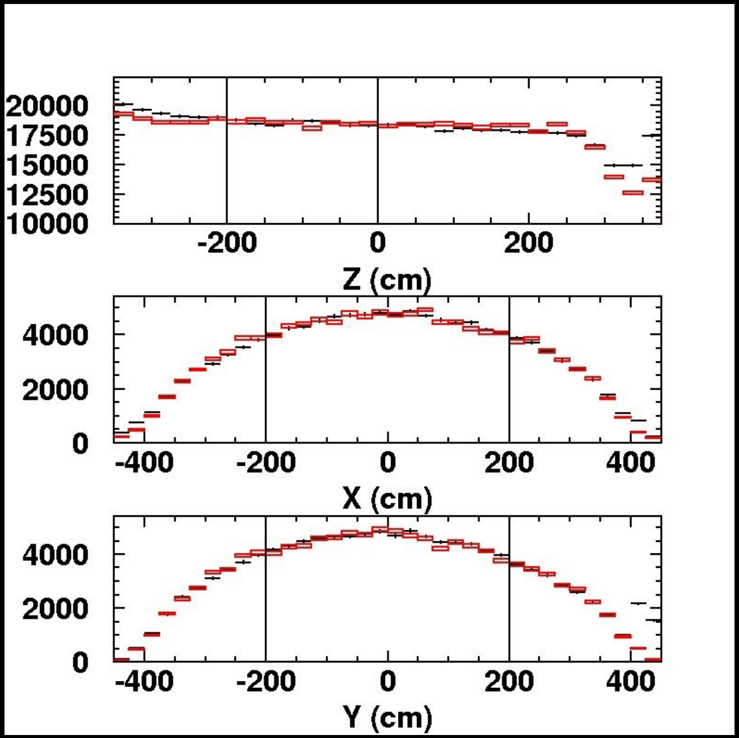
Measure number of interactions and energy spectrum

Oscillation analysis ($\sin^2 2\theta$, Δm^2)

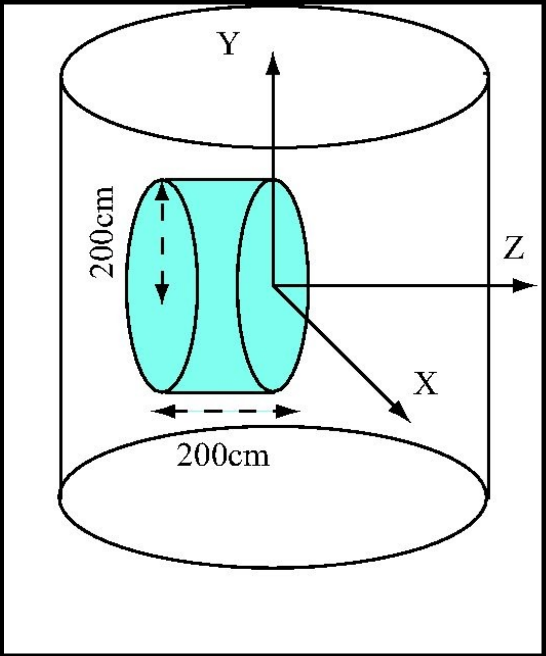
Predict unoscillated number of interactions and energy spectrum

Rate Measurement With Near Detectors

1KT interactions across fiducial



flux · xsec



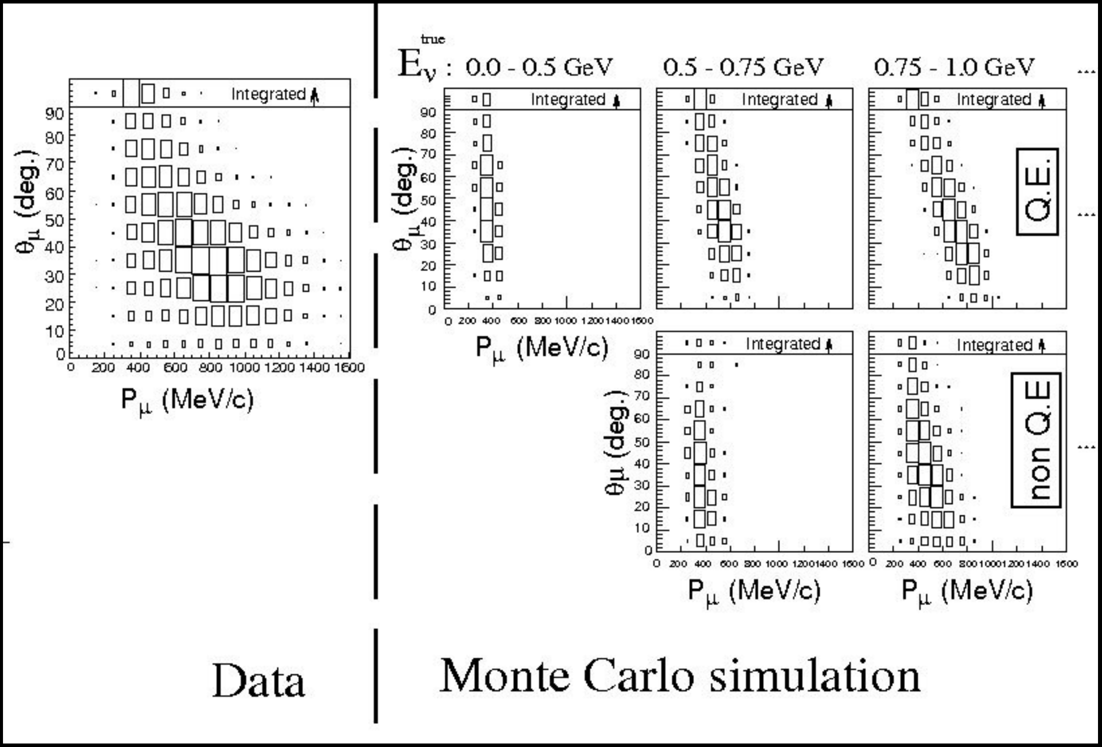
- Total number of neutrino interactions in 1KT 25 ton fiducial volume, correcting for:
  - Multiple interactions per spill, rejected due to problematic reconstruction
  - Selection efficiency (energy threshold)
  - Small background fraction from cosmic rays and beam-induced muons

- Infer number of interactions of all energies and types in 1KT
- 4.1% uncertainty in calculation, dominated by fiducial volume uncertainty

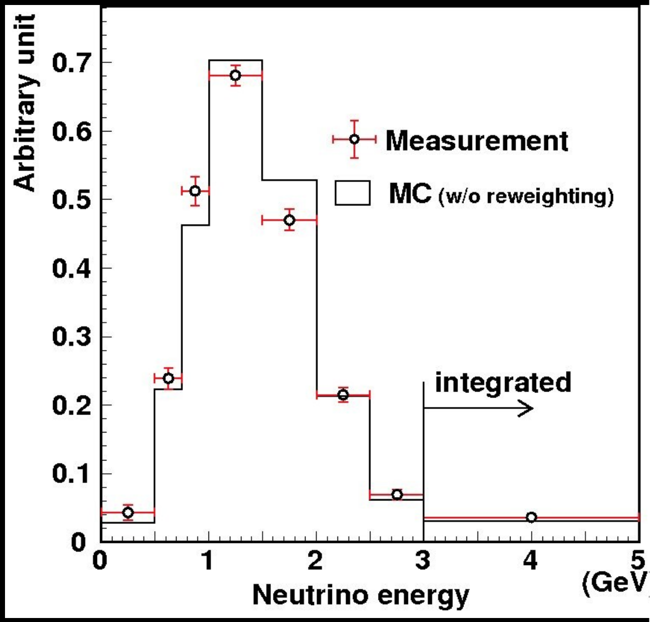
Energy Spectrum and non-QE Interactions With Near detectors

- (p_μ,θ_μ) distributions in charged current events from 1KT, SciFi and SciBar to tune:
  - energy spectrum
  - rate of inelastic interactions: R_{nqe} = (CC-non-QE/CC-QE)$_{data}$/(CC-non-QE/CC-QE)$_{MC}$
- For CC-QE interactions: (p_μ,θ_μ) <-> E_ν from 2-body kinematics
- SciFi, SciBar: clean discrimination of quasi-elastic from inelastic interactions, from kinematics in sub-samples with 2 reconstructed tracks

(p_μ,θ_μ) distributions vs energy, nQE/QE

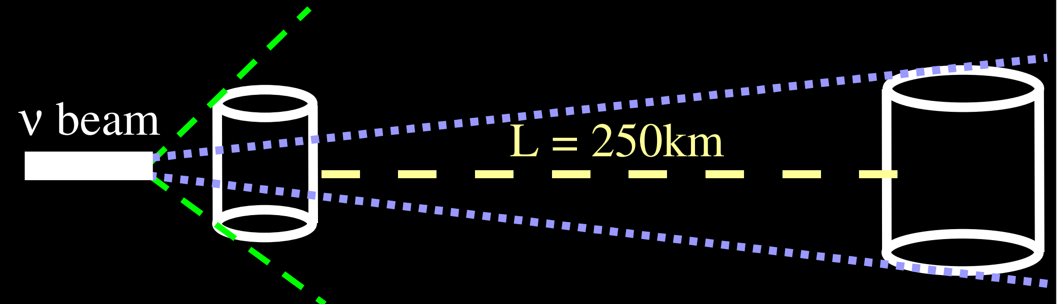


R_{nqe} = 0.96 ± 0.20

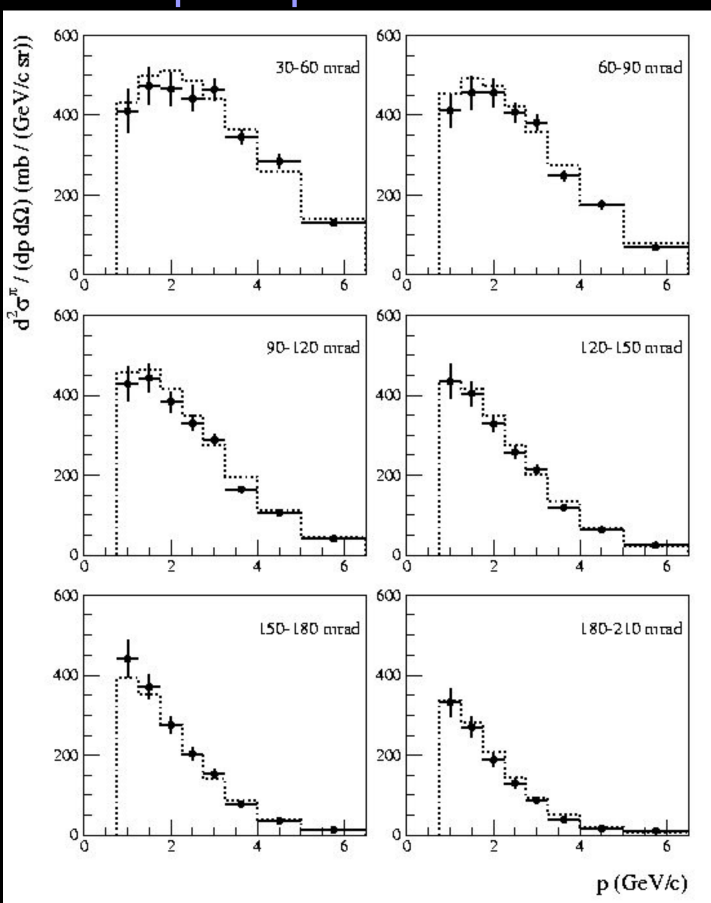


Flux Extrapolation From Near To Far Detector

- Extended source near detector correction, near/far different angular acceptance: characteristic “dip” in F/N ratio energy dependence, which could fake oscillations

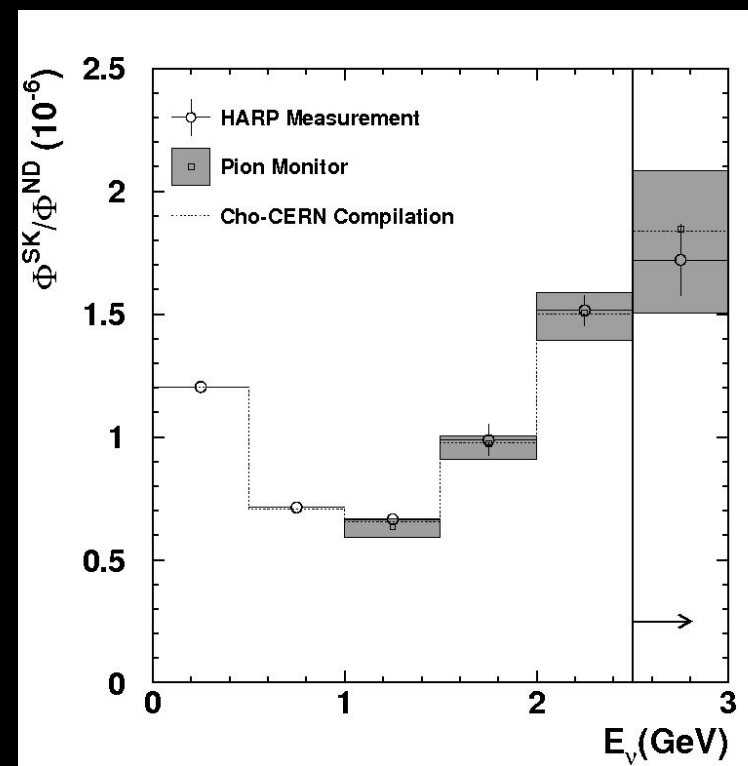


HARP pion production data



Tune beam MC with HARP, cross-checked (for E_ν>1 GeV) by in-situ PIMON measurement

Far-to-near flux ratio



No-Oscillation Predictions at Far Detector

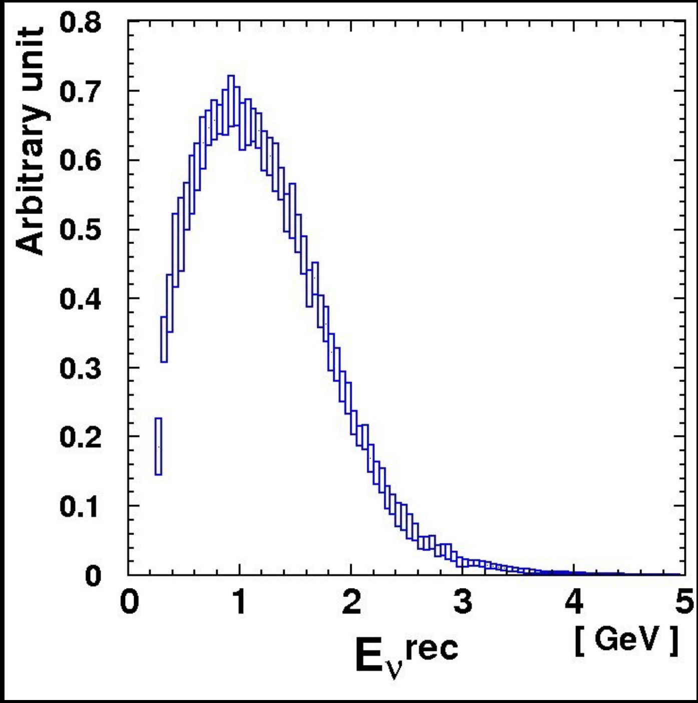
Number of Neutrino Events

- All fully contained events at SK in 22.5 kton fiducial volume
- Estimate number of events N_{SK} for no oscillations from 1KT observed rate, correcting for:
  - ratio of $\Phi\cdot\sigma\cdot\varepsilon(E_\nu)$ at 1KT and SK, where $\Phi^{SK}=R^{F/N}(E_\nu)\Phi^{ND}(E_\nu)$
  - ratios of 1KT and SK fiducial masses and protons on target used
  - difference in ν_e contamination in the beam at 1KT and SK
- For entire data run, expect:

$$N_{\mathrm{exp}}^{\mathrm{SK}} = 158.1^{+9.2}_{-8.6}$$

Neutrino Energy Spectrum

- Fully contained, 1-ring μ-like events in 22.5 kton fiducial volume only, for better neutrino energy reconstruction
- Folding shape information from flux, cross section, SK efficiency, pdf(E_ν^{rec},E_ν) together, expect for no oscillations:



Oscillation Analysis and Systematic Uncertainties

- Maximum-likelihood fit with normalization and energy shape terms, returning ($\sin^2 2\theta$, Δm^2) oscillation parameters affecting SK predictions
- Pull-term analysis: ~30 additional fit parameters, parametrizing systematic effects, constrained by a third likelihood term describing uncertainties on those

Number of Neutrino Events

- Largest systematic uncertainty contribution due to fiducial volume uncertainty in 1KT and SK:

$$\delta N_{\text{exp}}^{\text{SK}} = {}^{+4.9\,\%}_{-4.8\,\%}$$

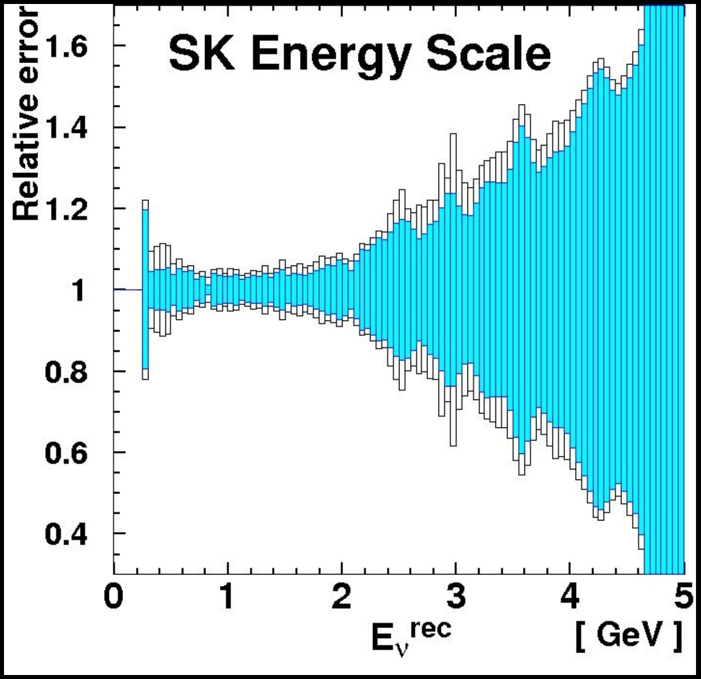
- Second largest contribution due to near-to-far flux extrapolation:

$$\delta N_{\text{exp}}^{\text{SK}} = \pm 2.9\,\%$$

(Before HARP: ±5.1%)

Neutrino Energy Spectrum

- Systematic uncertainty dominated by SK 2.0% energy scale uncertainty:



Rate and Spectrum Measurement at Super-Kamiokande

Number of Neutrino Events

- Reject beam-unrelated backgrounds, and partially contained and poorly reconstructable beam-induced interactions, by requiring:
  - no activity prior to beam
  - above PE threshold
  - no outer detector activity
  - no PMT "flashers"
  - above visible energy threshold
  - in fiducial volume
  - in time with beam
- Observe **112** events, to be compared with $158.1^{+9.2}_{-8.6}$ expectation for no oscillations

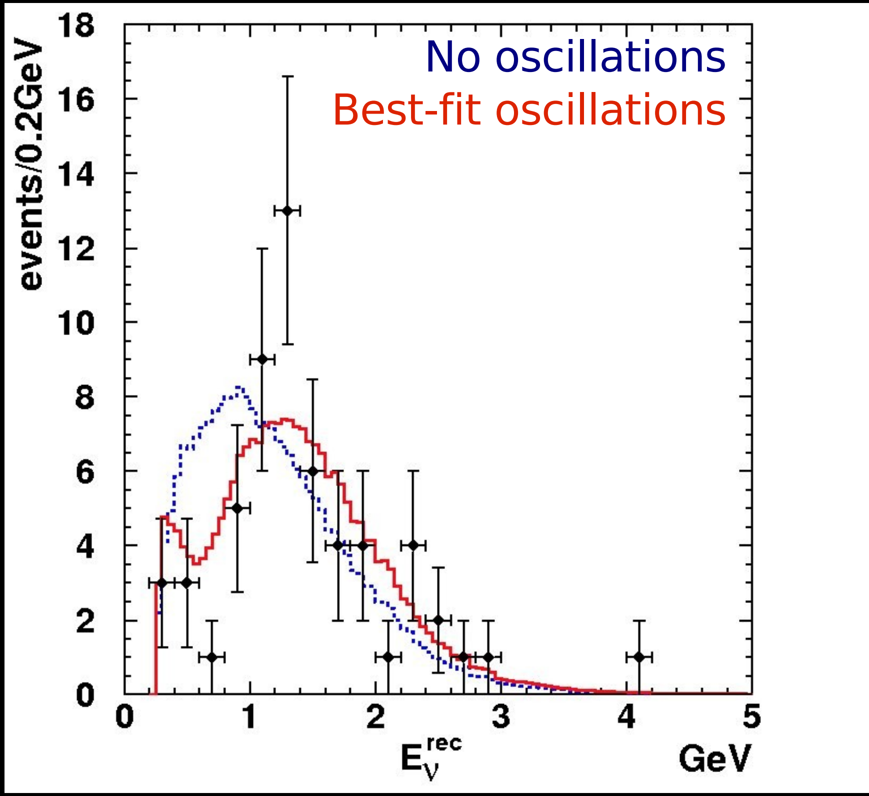
Ref: K2K Coll, PRD74:072003 (2006)

Neutrino Energy Spectrum

- Further require that events are reconstructed as 1-ring μ-like:

58 out of 112

- Neutrino energy spectrum shape consistent with oscillations



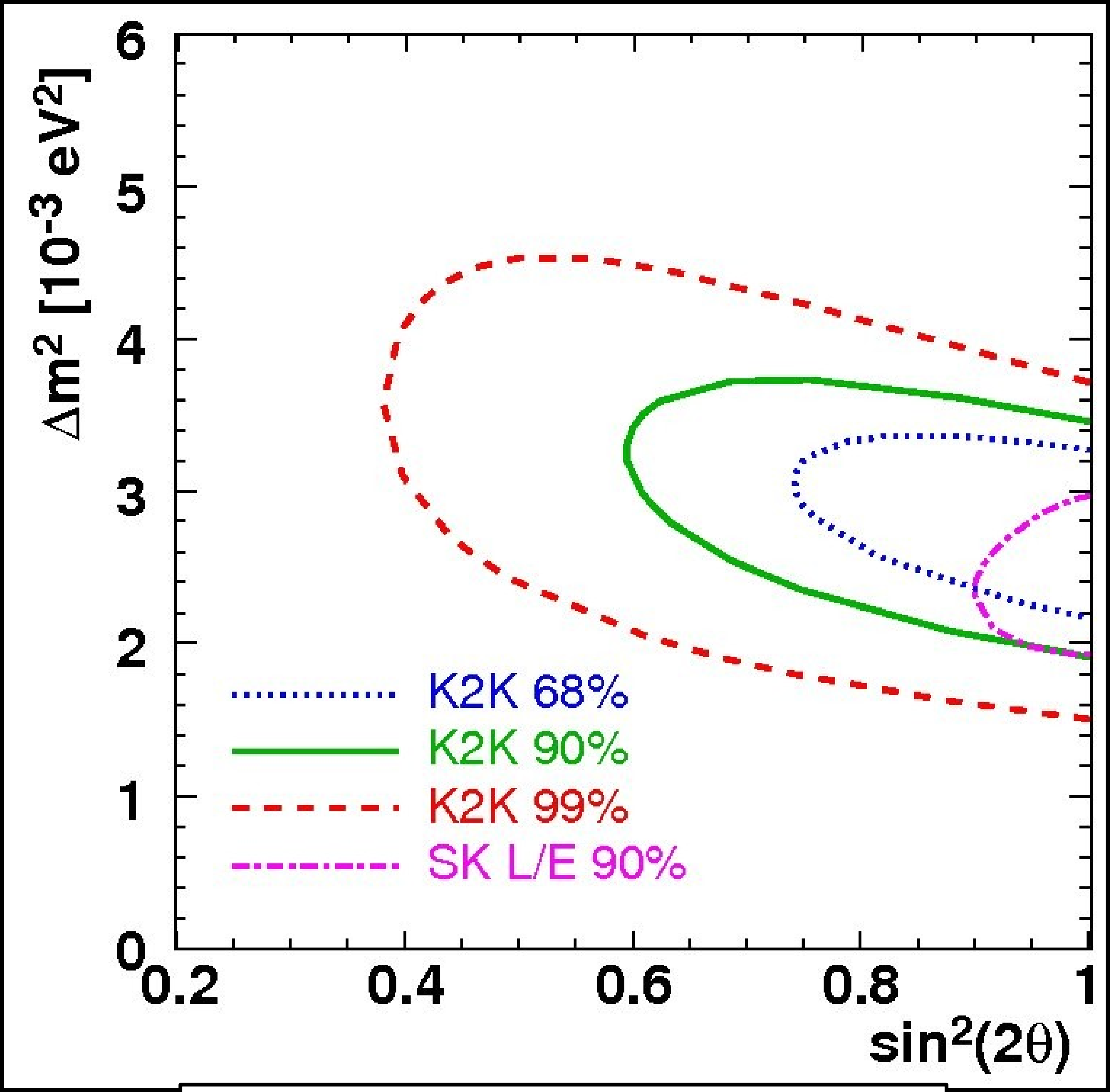
Neutrino Oscillation Significance and Systematics

Null oscillation probability: probability that null oscillation and best-fit oscillation hypotheses describe K2K data equally well. Can be converted into number of sigmas

Errors Considered	Oscillation Significance (# sigmas)		
	Rate Only	Spectrum Only	Combined
Statistical Error Only	3.9	3.1	4.9
Stat. + near detector spectrum	3.9	3.0	4.8
Stat. + nQE/QE, NC/CC xsec	3.9	3.0	4.8
Stat. + far-to-near flux ratio	3.7	3.0	4.7
Stat. + SK 1-ring μ-like efficiency	N/A	3.0	4.8
Stat. + SK energy scale	N/A	2.9	4.8
Stat. + SK/1KT normalization	3.6	N/A	4.6
All Errors	**3.4**	**2.9**	**4.3**

- Significance of oscillations: 4.3 sigma (rate-only: 3.4, spectrum-only: 2.9)
- K2K is statistics-limited: if systematics were negligible, 4.9 sigma significance instead

Measurement of Neutrino Oscillation Parameters



Ref: K2K Coll, PRD74:072003 (2006)

- K2K best-fit oscillation parameters:

$\Delta m^2 = 2.75 \cdot 10^{-3}$ eV^2, $\sin^2 2\theta = 1.00$

- K2K measurement compatible with SK atmospheric and MINOS (not shown here)

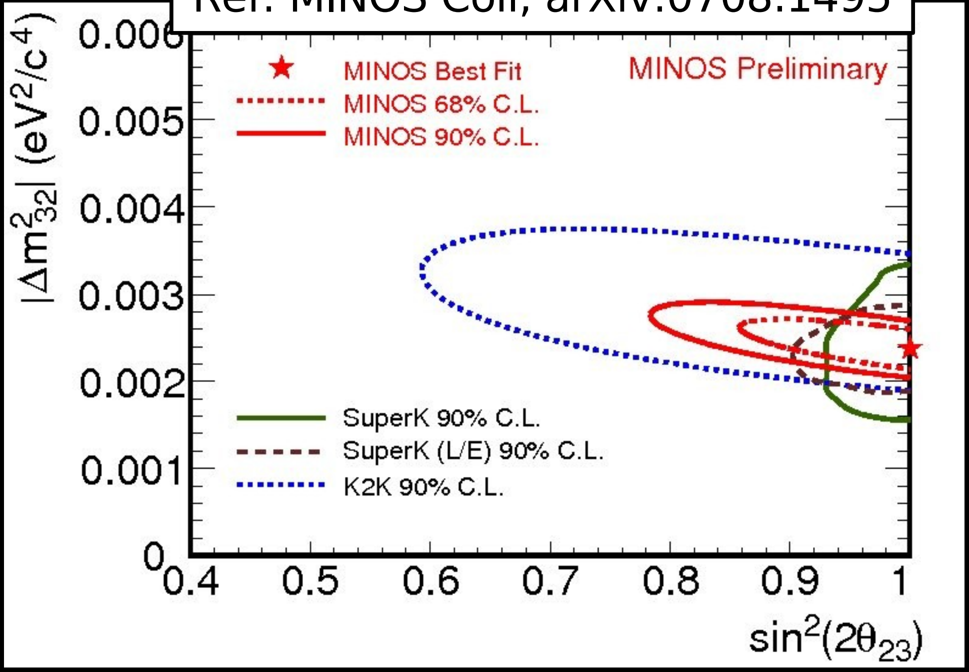
- K2K cross-checks:
  - all systematic pull-terms are reasonable
  - rate-only and spectrum-only measurements are compatible
  - results before/after SK accident are compatible

Atmospheric $\nu_\mu \to \nu_\tau$ Oscillations: The Other Players

MINOS

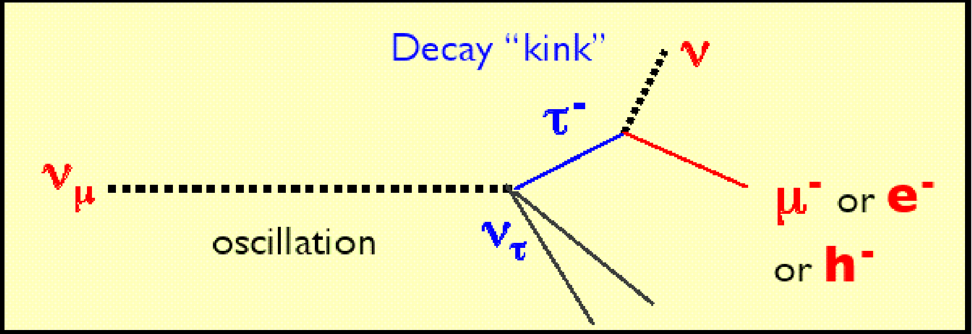
- Data-taking started in 2005
- $\langle E_\nu \rangle$ = 5 GeV, L=735 km
- Magnetized tracking calorimeter
- First results in 2006; significant improvement over K2K from latest 2007 results

Ref: MINOS Coll, arXiv:0708.1495



OPERA

- First low-intensity CNGS run in 2006, next run this year
- $\langle E_\nu \rangle$ = 17 GeV, L=730 km
- Emulsion/tracking detector
- Look for direct ν_τ appearance by detecting τ decays following charged current interactions



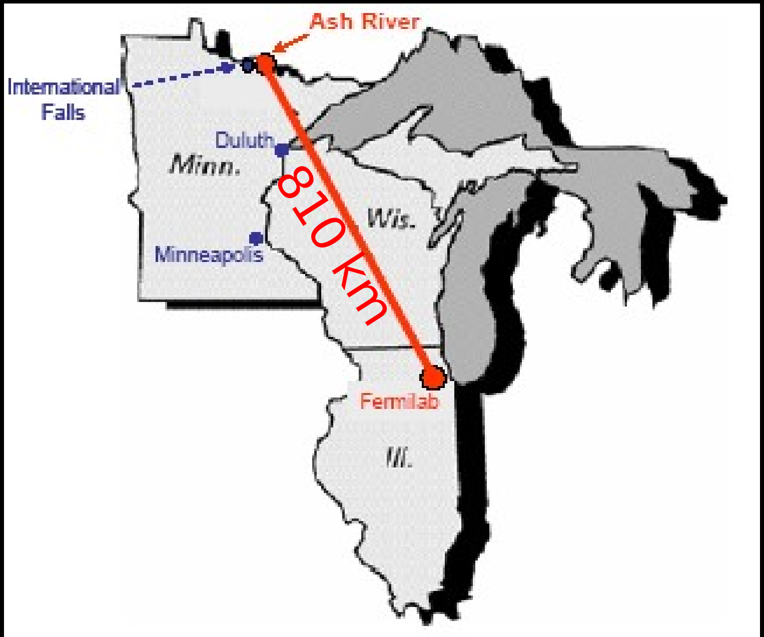
Atmospheric $\nu_\mu \to \nu_\tau$ Oscillations: The Other Players

T2K

- Beam and near detectors under construction, far detector ready
- Data-taking expected start date: 2009
- $<E_\nu>$ = 0.8 GeV, L=295 km
- Far detector: water Cherenkov (SK-III)
- 2.5 deg off-axis beam

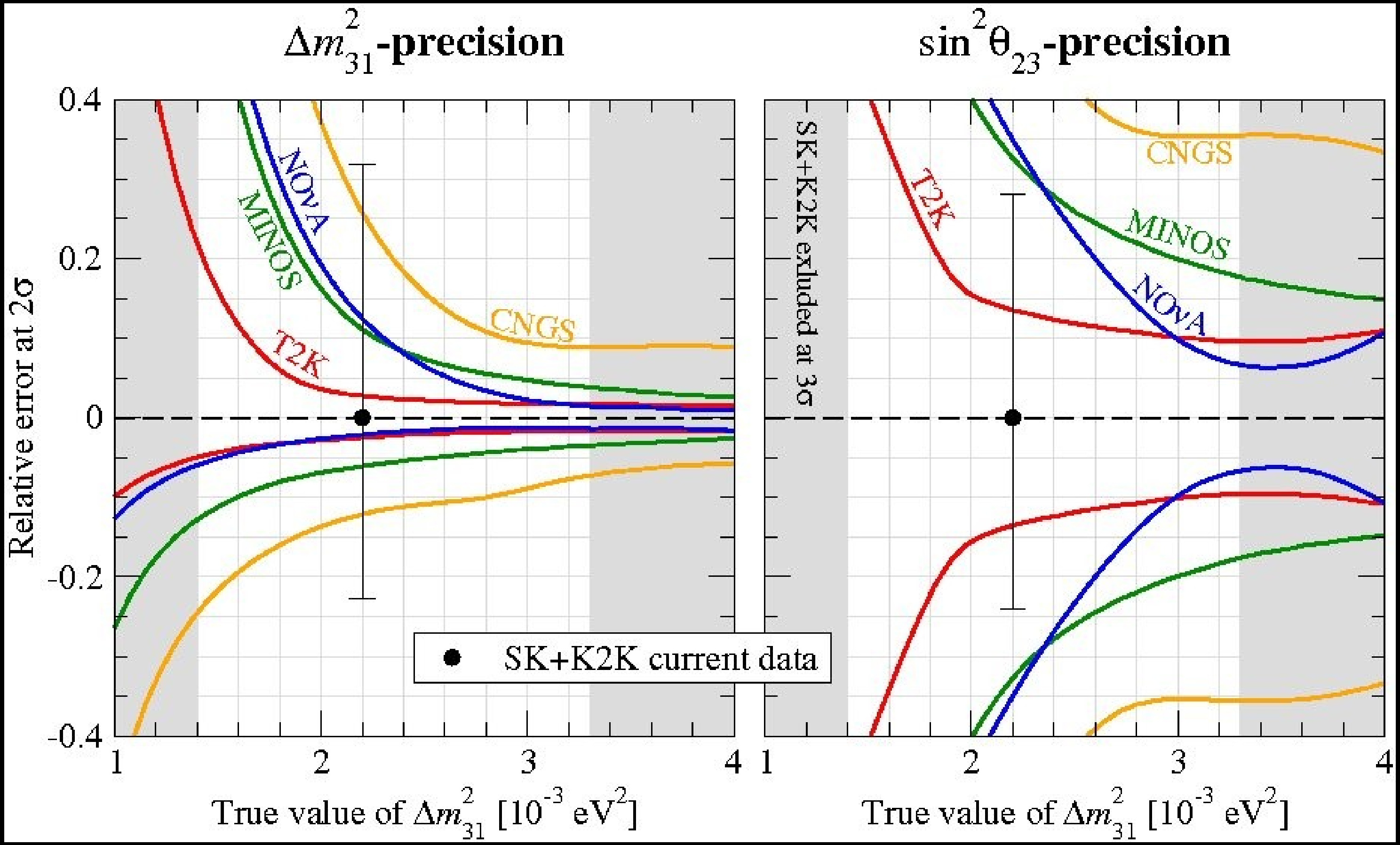
NOνA

- Design being finalized, integration detector prototype in 2008
- Data-taking expected start date: 2011
- $<E_\nu>$ = 2.2 GeV, L=810 km
- Liquid scintillator detector
- 0.8 deg off-axis beam



Near-Term Sensitivity Reach in Δm^2_{31} and θ_{23}

- Over the next five years, should reach:
  - Few % accuracy on Δm^2_{31}. Order-of-magnitude improvement, important for planning next-generation oscillation experiments
  - 1-2% accuracy on $\sin^2 2\theta_{23}$, translating into 5-10% accuracy on $\sin^2 \theta_{23}$. More modest improvement



Ref: Gonzalez-Garcia, Maltoni, arXiv:0704.1800

K2K Disappearance Measurement: Lessons Learned

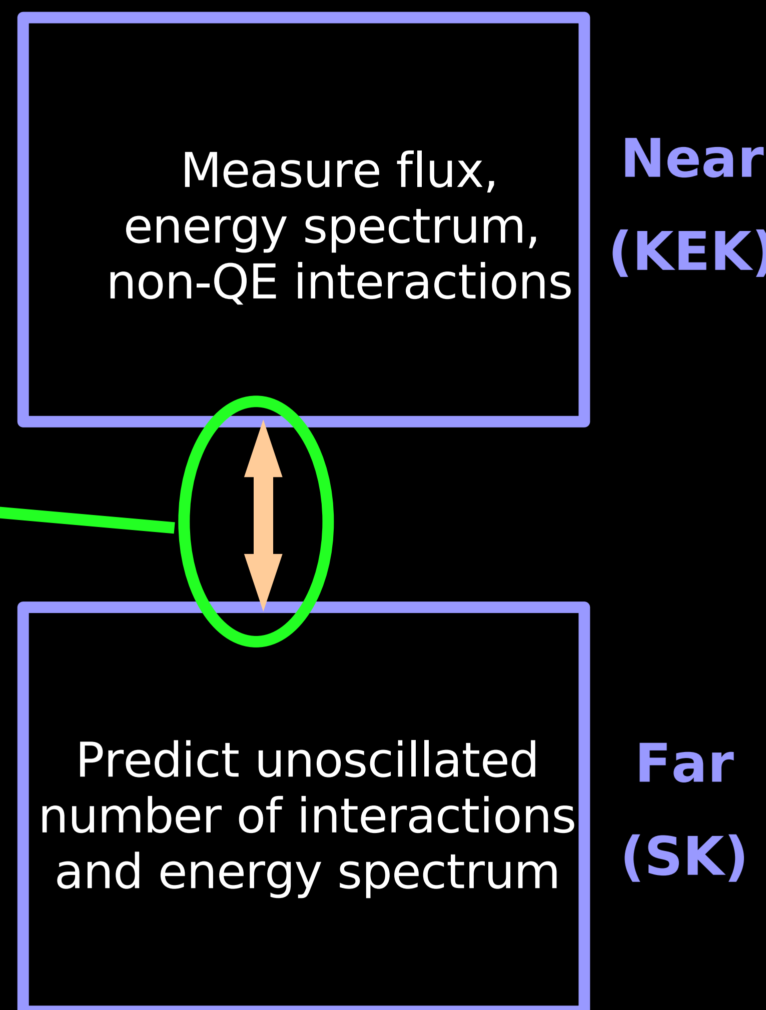
Near (KEK)

Measure number of neutrino interactions and (p_μ, θ_μ) distributions

Measure flux, energy spectrum, non-QE interactions

- Primary, secondary, neutrino beam monitoring (pointing, etc.)
- Accurate knowledge of near detector fiducial mass
- Precision measurement of all relevant interaction channels, cross-sections energy dependence. Need to reconstruct pions and protons. Stay away from resonant production and low-Q^2 regions, unless you can measure them well
- Accurate knowledge of near detector energy scale. Similar energy calibration techniques as for far detector may help
- A near detector component that is a “miniature” version of far detector helps, particularly for overall rate suppression measurement

K2K Disappearance Measurement: Lessons Learned



- Near detector exposed to similar flux as far detector one, eg not too near. More advantageous for higher intensity beams

- Good understanding of kinematics for pions responsible for neutrino beam: external hadron production measurements, in-situ pion monitoring

K2K Disappearance Measurement: Lessons Learned

- **Statistics!**
- Accurate knowledge of far detector energy scale
- Accurate knowledge of far detector fiducial mass

Far (SK)

Measure number of interactions and energy spectrum ⟷ Predict unoscillated number of interactions and energy spectrum

Search for Sub-Leading

ν_μ -> ν_e Oscillations

Electron Neutrino Appearance Probability

- Probability that a neutrino produced with muon flavor and energy E will be detected as a neutrino of distinct electron flavor, after propagating a distance L = 250 km

- To first order at the atmospheric L/E scale, can also be described via a single oscillation frequency and oscillation strength:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{\mu e} \cdot \sin^2 (1.27\Delta m^2 L/E)$$

- Two-neutrino parameters can be associated to 3-neutrino mixing ones as:

$$\Delta m^2 \to \Delta m^2_{31}, \quad \sin^2 2\theta_{\mu e} \to \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13}$$

- Corrections due to small parameter Δm^2_{21}L/E, matter density and CP-violating phase δ are small

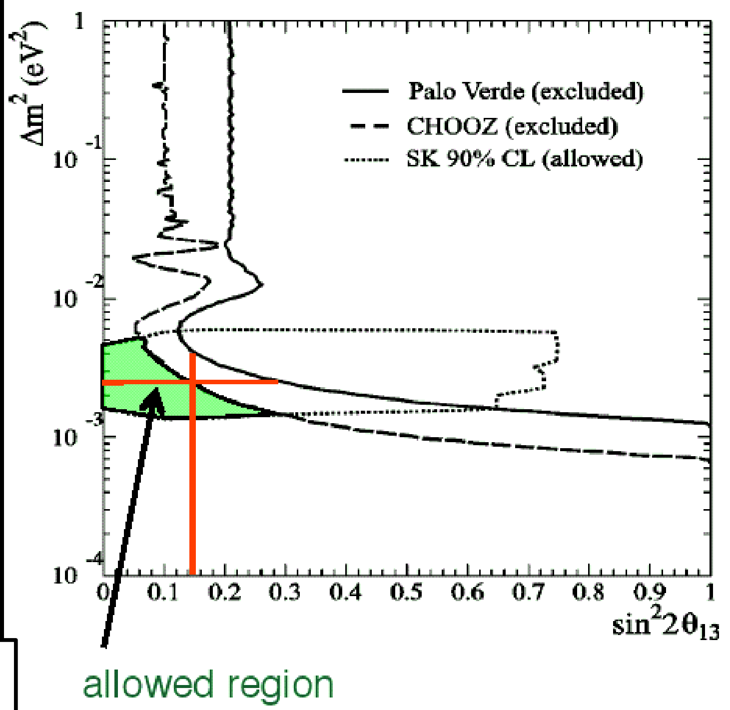
- The same mixing angle θ_{13} can be probed by measuring the survival probability of electron antineutrinos produced by reactors at a km-scale distance from the source:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2 (1.27\Delta m^2_{31} L/E)$$

θ_{13} Knowledge from Reactor, Solar, Atmospheric Data

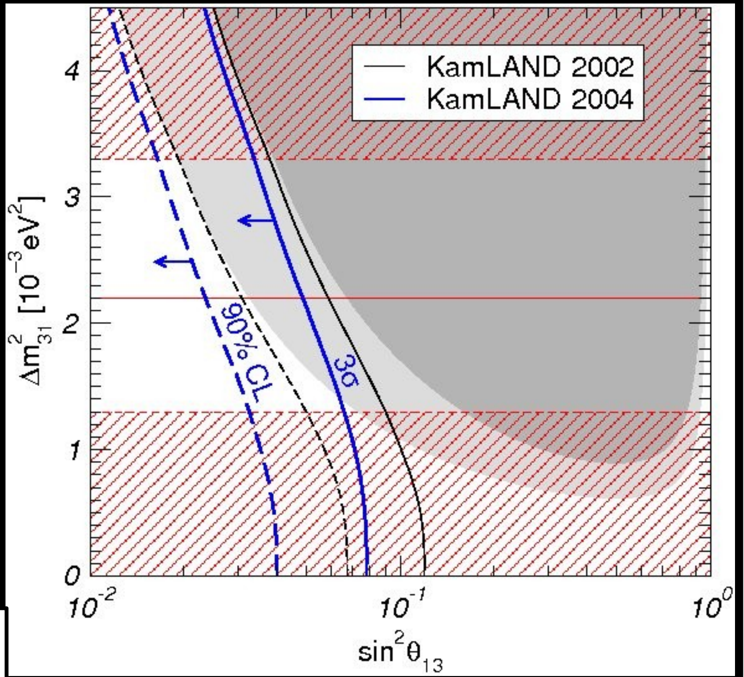
- Direct search at CHOOZ (and Palo Verde) reactor:

$\sin^2 2\theta_{13} < 0.15$ at 90% C.L., for $\Delta m^2_{31}=2.5\cdot10^{-3}$ eV^2



Ref: CHOOZ Coll, EPJ C27: 331 (2003)

- Comparable limit obtained from solar, KamLAND, and atmospheric data in global 3 neutrino fits
- Overall, we know that $\sin^2 2\theta_{13}$ is less than about 0.1
- The θ_{13} mixing angle can also be constrained in long-baseline accelerator experiments, looking for $\nu_\mu \rightarrow \nu_e$ oscillations -> **K2K**

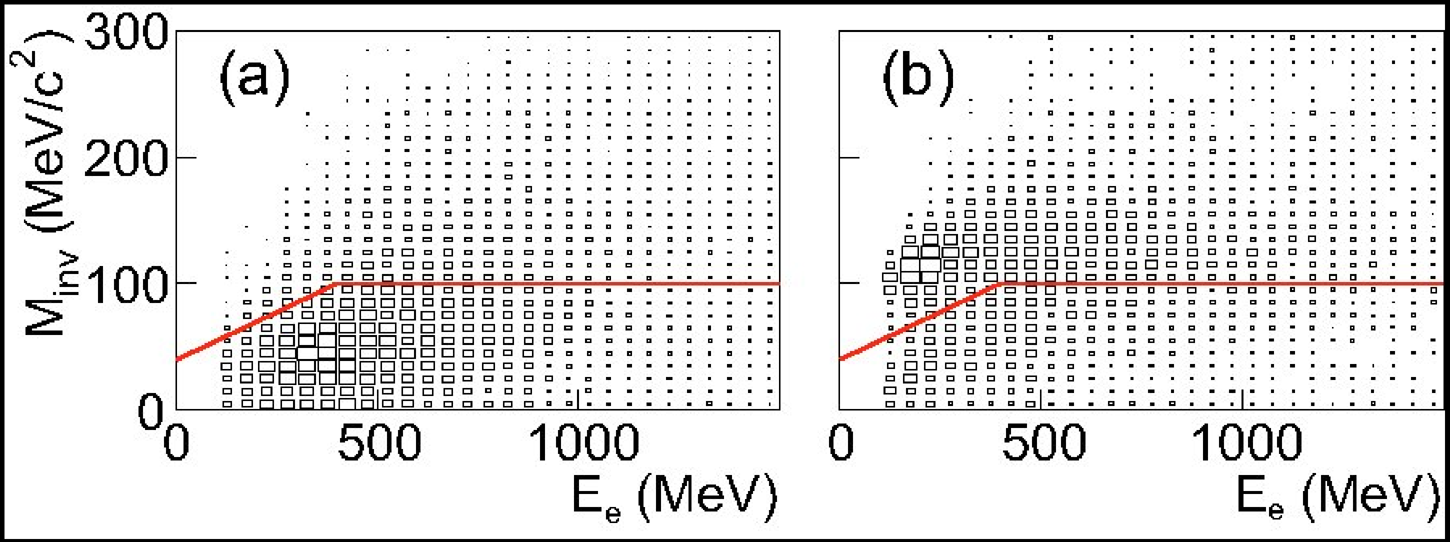


Ref: Valle, arXiv:hep-ph/0509262

K2K Event Selection and Background Events

- Signal: $\nu_e n \to e^- p$. Experimental signature: single ring, showerlike event from electron
- Backgrounds:
  - mis-identified ν_μ interactions (mostly $\nu_\mu N \to \nu_\mu N\pi^0$)
  - ν_e contamination in the beam
- Showerlike event, as determined from shape of Cherenkov ring pattern and opening angle
- Non-π^0 like event, from event's invariant mass (2-ring hypothesis) and visible energy

Signal (MC) **ν_μ background (MC)**



Event Selection and Background Events

- Signal: $\nu_e n \rightarrow e^- p$. Experimental signature: single ring, showerlike event from electron
- Backgrounds:
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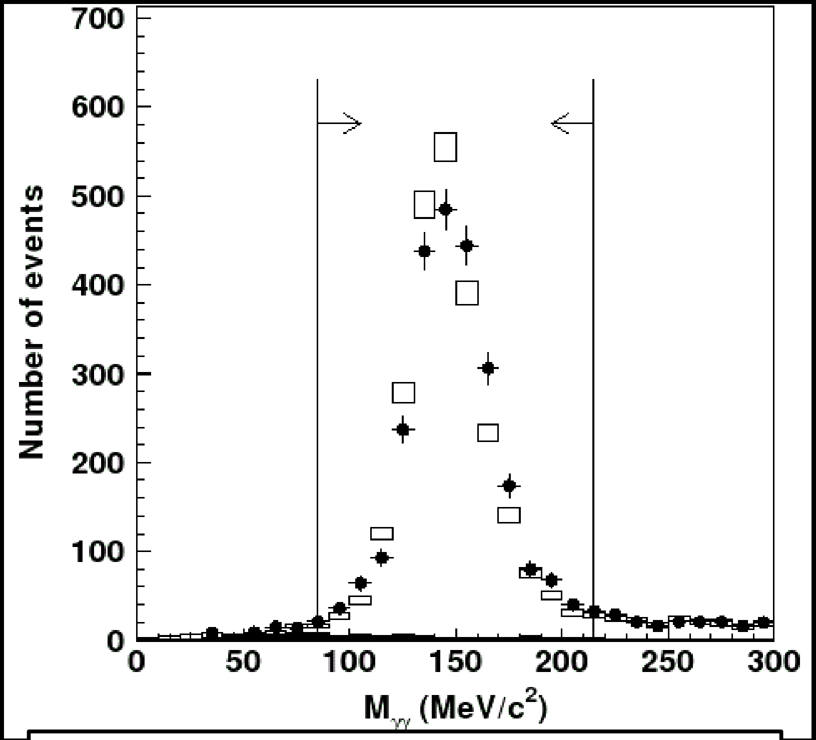
  - ν_e contamination in the beam
- Showerlike event, as determined from shape of Cherenkov ring pattern and opening angle
- Non-π^0 like event, from event's invariant mass (2-ring hypothesis) and visible energy

Requirement	ν_μ no-osc background	ν_e background
Fully contained, in fiducial	158.5	1.7
Single ring	99.5	1.0
Showerlike	5.9	0.8
Minimum visible energy	5.4	0.8
No decay electron	4.1	0.7
Non-π^0 like	**1.3**	**0.4**

Background Estimates

- Common with disappearance analysis:
  - ν energy spectrum and normalization from near detector measurements
  - near-to-far flux extrapolation from beam simulation based on HARP data

1KT NC-1π^0 sample



Ref: K2K Coll, PL B619:255 (2005)

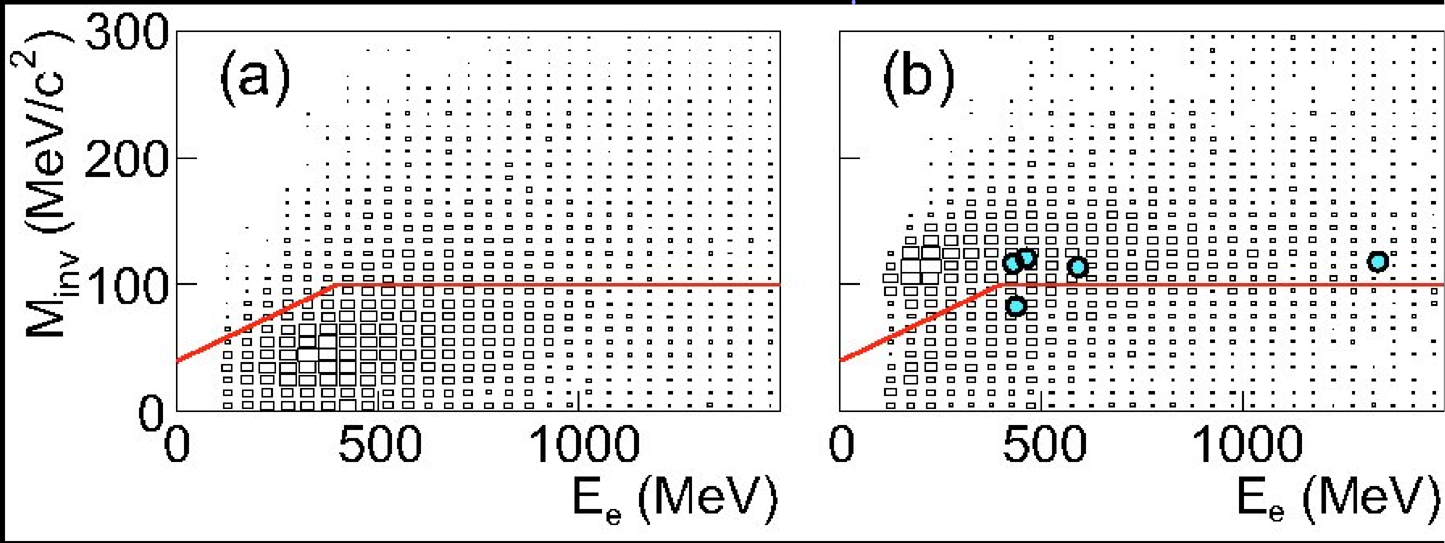
- Specific for this analysis:
  - Expectation for beam ν_e contamination cross-checked with 20-25% accuracy
  - rate and spectrum of $\nu N \rightarrow \nu N \pi^0$ background constrained from 1KT
  - ~30% systematic uncertainty on total background expectation, most significant contribution related to π^0 rejection cuts

Electron-Like Events

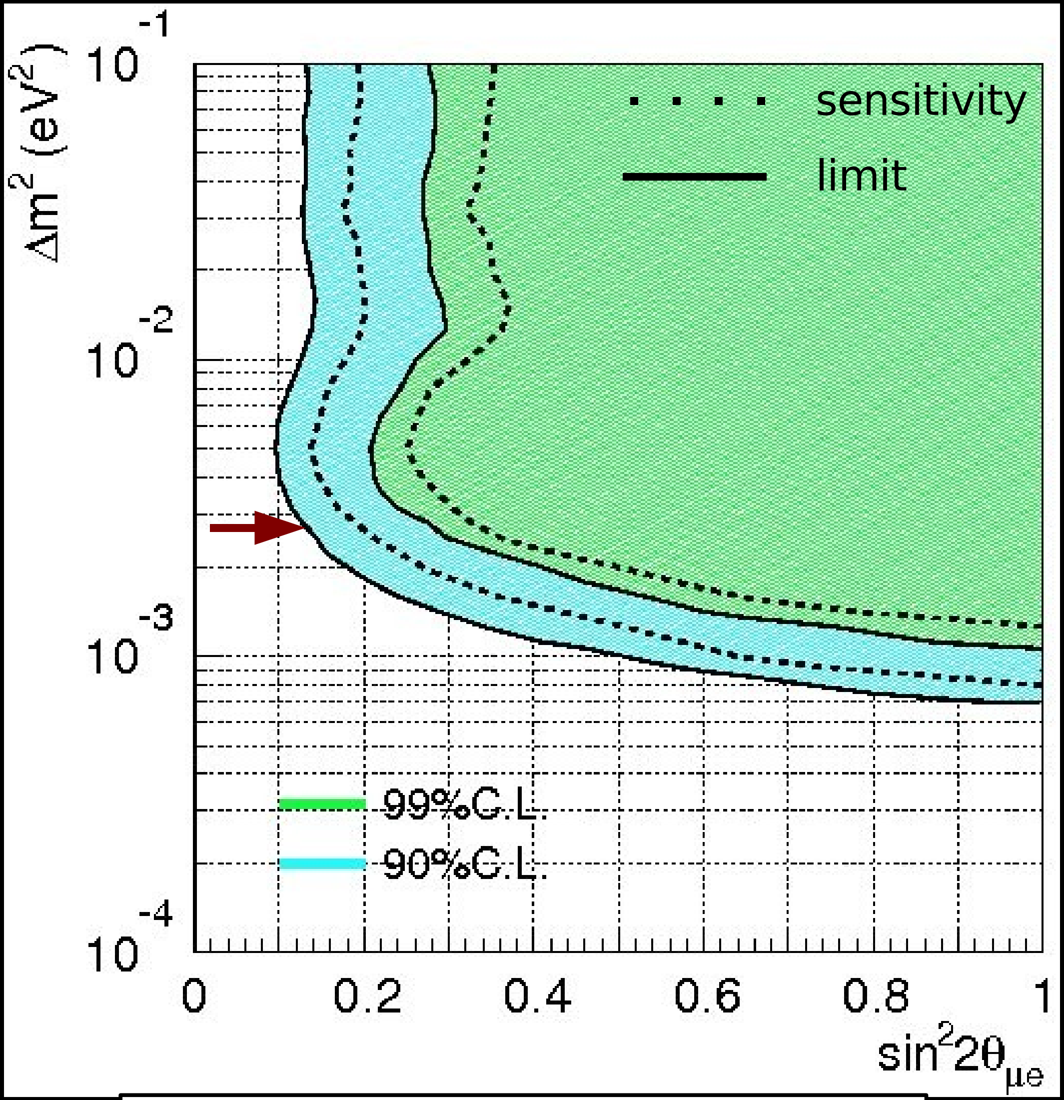
Requirement	ν_μ no-osc background	ν_e background	Data
Fully contained, in fiducial	158.5	1.7	112
Single ring	99.5	1.0	67
Showerlike	5.9	0.8	8
Minimum visible energy	5.4	0.8	7
No decay electron	4.1	0.7	5
Non-π^0 like	**1.3**	**0.4**	**1**

- One electron-like event selected in data, in agreement with 1.7 background expectation

Signal (MC) ν_μ background vs Data



Appearance Results



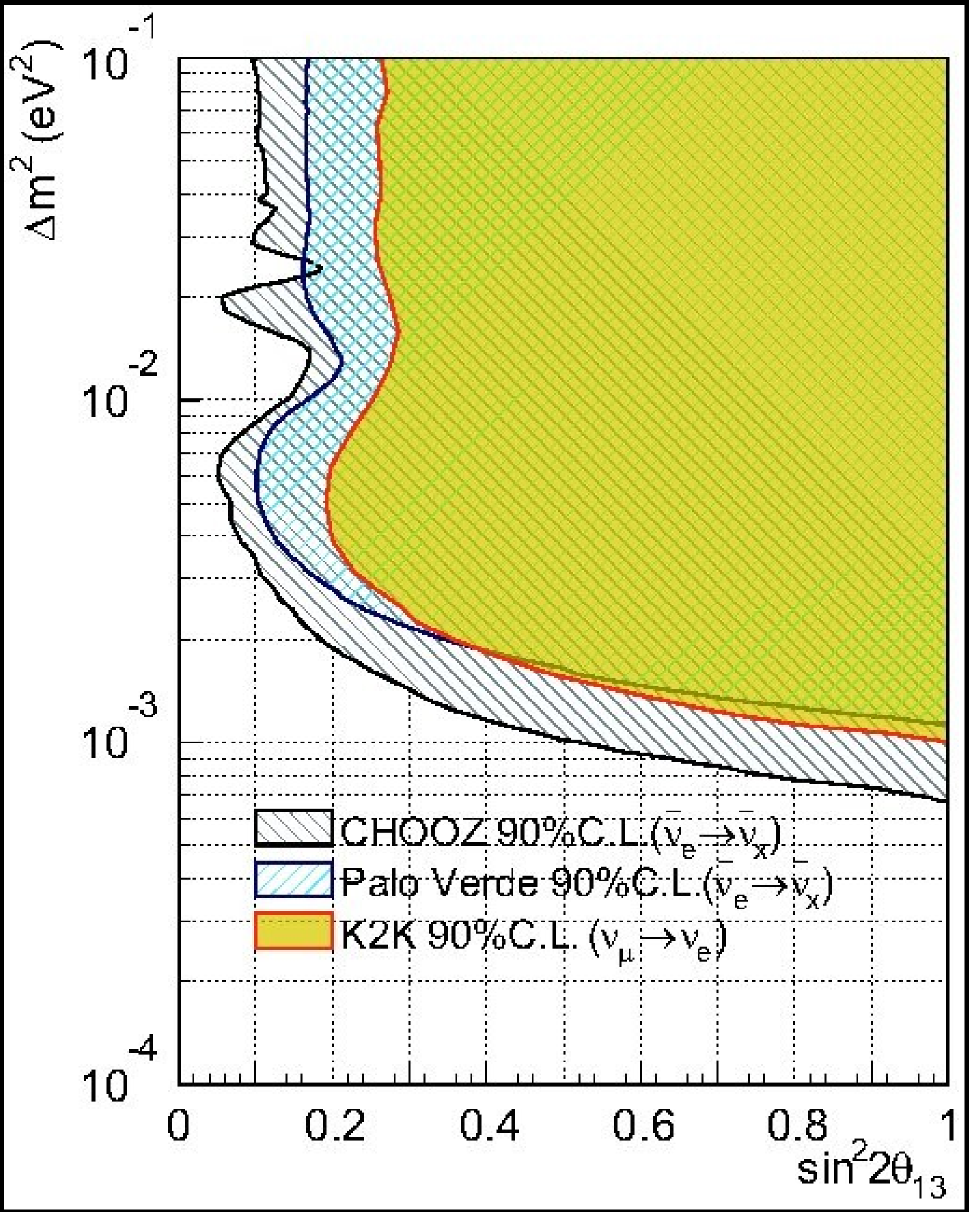
Ref: K2K Coll, PRL 96:181801 (2006)

- K2K excludes $\nu_\mu \rightarrow \nu_e$ oscillations with oscillation strength:

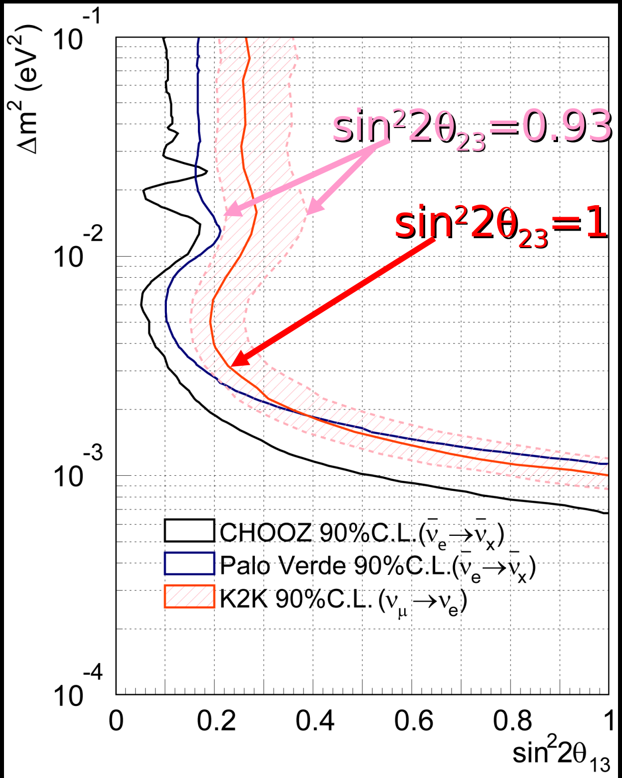
$$\sin^2 2\theta_{\mu e} > 0.13$$

at $\Delta m^2 = 2.8 \cdot 10^{-3}$ eV^2 and 90% confidence level

Comparison With Reactor Limits



- $\sin^2 2\theta_{\mu e} \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \approx \sin^2 2\theta_{13} / 2$
- K2K limit less stringent than reactors' by about a factor of 2
- Comparison depends upon true value of $\sin^2 \theta_{23}$, not too precisely known



Search for θ_{13}: The Other Players

MINOS:

- *"Sensitivity will soon be comparable with CHOOZ limit"*
- Much effort underway for discriminating electromagnetic from hadronic showers, data-driven techniques for background determination

Double Chooz reactor experiment:

- In final R&D phase
- Data-taking with far detector in 2008
- Near and far detectors in 2010

Daya Bay reactor experiment:

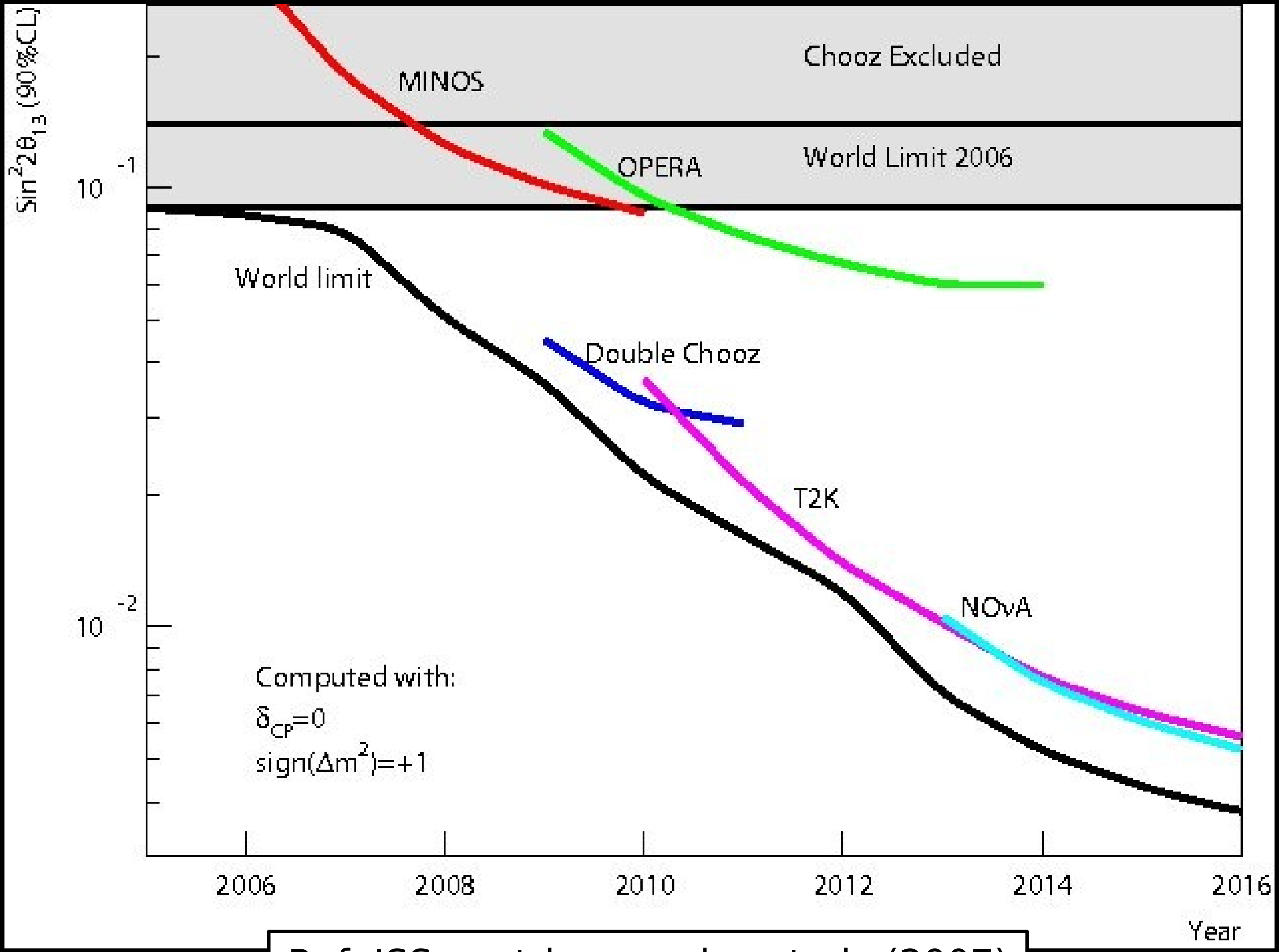
- Begin civil construction this year
- Data-taking with complete detector configuration starts in 2010-2011
- Can go beyond Double Chooz sensitivity

T2K and NoνA:

- Optimized for sensitive $\sin^2 2\theta_{13}$ search, main physics goal for their first phase of operation (2009-2015)

Sensitivity Reach in θ_{13}

- Over the next 6-7 years, should reach order-of-magnitude better sensitivity in $\sin^2 2\theta_{13}$ relative to current limit



Ref: ISS neutrino scoping study (2007)

K2K Appearance Measurement: Lessons Learned

- For order-of-magnitude better sensitivity in $\sin^2 2\theta_{13}$ over current limit with accelerators, need everything mentioned for disappearance measurement, plus:
- **MUCH MORE STATISTICS!** (1-2 orders of magnitude more)
- Improve signal-to-background ratio by ~ order of magnitude:
  - reduce π^0 production rate relative to CCQE with different beam, better π^0 rejection
  - reduce beam ν_e fraction in relevant energy range
- Background control:
  - π^0 production rate and kinematics measurement, good understanding of π^0 reconstruction and rejection
  - Measurement of beam ν_e contamination across all energies (also low) and energy dependence, hadron production measurement of kaons
- Precise measurement of disappearance parameters ($\sin^2 2\theta_{23}$, Δm^2_{31}) help for the interpretation of the appearance results

Conclusions

- K2K pioneered the technique for the exploration of neutrino masses and mixings with accelerator-based neutrino beams detected hundreds of km away from source

- K2K confirmed atmospheric neutrino oscillations by measuring ν_μ disappearance and spectral distortion, compared to no oscillations :
  - 4.3σ evidence for neutrino oscillations
  - Measurement of oscillation parameters consistent with atmospheric neutrinos

- K2K search for sub-leading ν_μ -> ν_e oscillations paved the way for designing next-generation conventional accelerator-based experiments, to complete the neutrino picture:
  - Value of last unknown neutrino mixing angle θ_{13}?
  - Is there leptonic CP violation? Neutrino mass hierarchy?